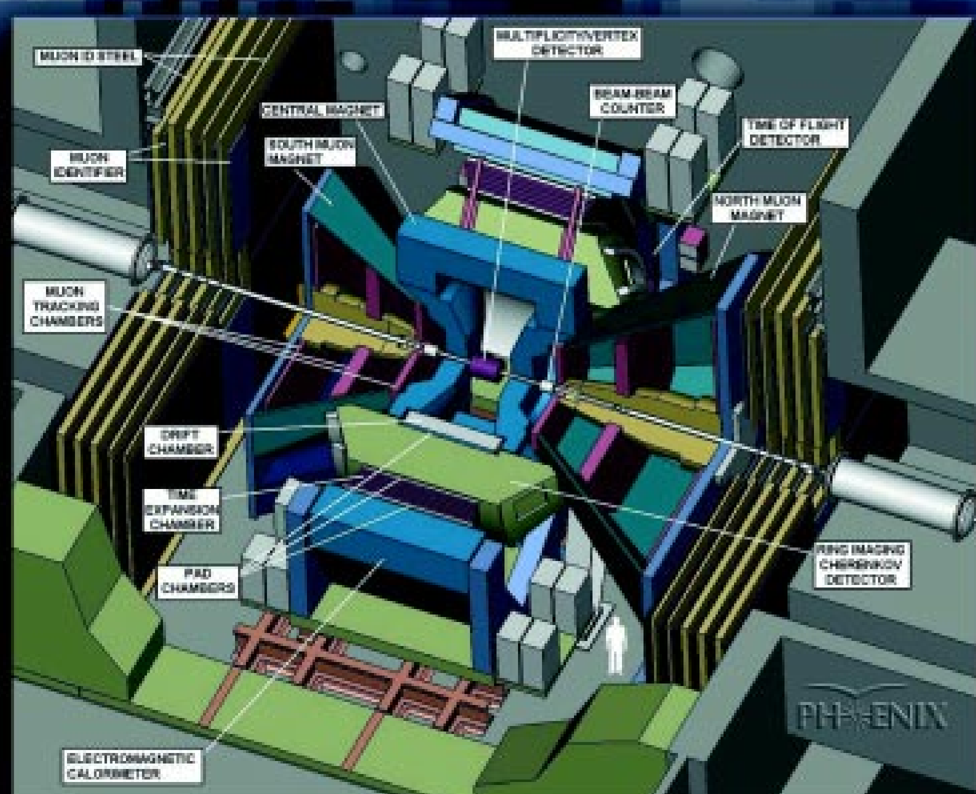
1. Group Descriptions



Physics Division has a major role in constructing two major subsystems for the Pioneering High Energy Nuclear Ion Exeperiment (PHENIX) detector at Brookhaven's Relativistic Heavy-Ion Collider (RHIC): the multiplicity/vertex detector and the muon subsystem. Both of these systems play crucial roles in the RHIC physics agenda, which aims to explore the exotic properties of quark-gluon plasmas like those that existed early in the evolution of the universe.

P-21: Biophysics

C. C. Wood, Group Leader

Introduction

The Biophysics Group (P-21) was founded in 1988 with the goal of applying the scientific and technical resources of Physics Division to the biosciences. Our mission is to contribute to an understanding of biological phenomena by means of the scientific, technical, and conceptual resources of physics; to use biological systems to elucidate general physical principles underlying complex phenomena; and to apply, where appropriate, our scientific and technical capabilities to core Laboratory programs.

Just as the 20th century is regarded as the century of the physical sciences, the 21st century will likely become the century of the biological sciences. P-21 and biophysics as a discipline are well-positioned to contribute to this biological revolution-in-progress through our emphasis on understanding biological systems using the scientific, technical, and conceptual resources of physics.

Many of the achievements of science to date have come from a reductionist strategy, in which scientists attempt to decompose the object under study into ever simpler components and to understand those components with ever increasing quantitative precision. Physics has been particularly successful in this regard. In contrast, much of biology has traditionally been less quantitative and more descriptive in character, both because biological systems are so complex and because some of the key explanatory concepts lie at a more abstract level. Examples of such complex phenomena include coding and processing of genetic information by DNA, and information representation, coding, and processing by the nervous system. However, recent advances in biophysical measurement and in molecular biology are beginning to allow detailed physical understanding of biological phenomena that were previously understood only in qualitative terms.[1] P-21 is well placed by virtue of its capabilities and research interests to contribute significantly to this important trend in the biosciences.

In addition to the goal of achieving a physical understanding of biological phenomena, research in P-21 shares a number of other common characteristics. Specifically,

- we investigate the relationships between structure, dynamics, and function of biological phenomena over a wide range of scales (*e.g.*, from biomolecules through the human brain);
- we make extensive use of detection, imaging, and reconstruction techniques (*e.g.*, x-ray crystallography, single molecule electrophoresis, magnetic resonance imaging [MRI], and magnetic field measurements using technologies based on superconducting quantum interference devices [SQUIDs] as shown in Fig. 1);
- we attempt to achieve a detailed interplay between high-resolution physical measurement and large-scale computational modeling and analysis of complex systems;

- we develop new facilities in support of our scientific and technical goals, including a dedicated x-ray beam line for protein crystallography at the National Synchrotron Light Source (NSLS) at Brookhaven National Laboratory, a large-bore MRI facility, a high-speed electronics laboratory and fabrication facility, and a growing SQUID applications laboratory at Los Alamos;
- we depend heavily on the tight connection and daily interplay between biologists and physical scientists within the group, the division, and the Laboratory; and
- we apply the knowledge, techniques, and capabilities developed in our biological studies to problems of national security and those of specific interest to the Laboratory when our ongoing efforts can offer unique solutions and significant mutual benefit.

During the past two years, P-21 had a number of major accomplishments, including the addition and rapid integration of the world-class high-speed electronics team previously in the Hydrodynamics and X-Ray Physics Group (P-22), winning two of the Laboratory's total of four R&D 100 Awards for 1998, significant contributions to the formation of a new $60M National Foundation for Functional Brain Imaging, and helping to formulate and launch a new national research initiative in structural genomics. Our scientific and technical activity lies in six major areas, which are discussed individually below.

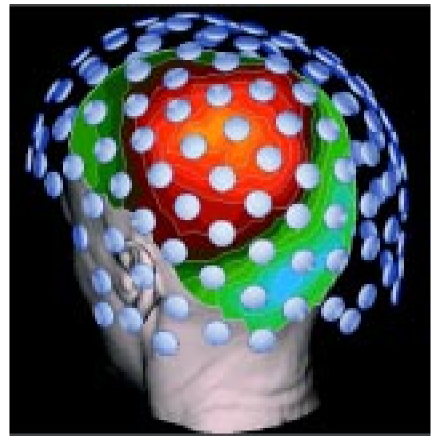


***Fig. 1** Our whole-head MEG system uses SQUID sensors to record the magnetic fields produced by active populations of neurons.*

Protein Structure, Dynamics, and Function

Our studies of protein dynamics aim to describe protein motion in atomic detail and understand the consequences of protein dynamics for protein function. We have extended our original work on kinetic x-ray crystallography of myoglobin[2] to the understanding of proteins important for bioremediation of trichloroethylene (TCE) and other soil and groundwater pollutants. P-21 is part of a multidisciplinary Los Alamos effort that seeks to enable bioremediation of TCE by genetically engineered microorganisms. The first step in this effort is obtaining a thorough understanding of the enzymatic mechanisms by which TCE can be degraded. In collaboration with scientists at universities across the country, as well as at the Max Planck Institute in Germany, P-21 scientists have begun to unravel the mystery surrounding the mechanism of one class of enzymes that might be engineered to degrade TCE: the cytochrome P-450s. P-450s bind molecular oxygen, split the dioxygen bond, and insert one oxygen atom into organic substrates. This can be the first step in the biodegradation of TCE. The reaction is also a crucial step in steroid hormone synthesis, and P450s are likely to be important in developing drugs to treat breast and other cancers.

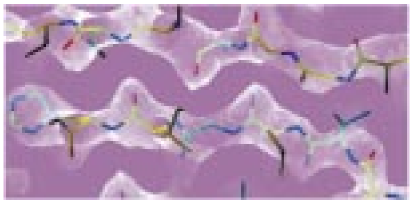


Fig. 2 An electron density contour map (pink) of an atomic model of that density (colored sticks). Solutions for protein structures such as this will be the primary emphasis of the protein crystallography program at the X8-C beamline.

To support our rapidly increasing efforts in protein crystallography, P-21 has converted beamline X8-C at the Brookhaven's NSLS to dedicated use for x-ray crystallography of proteins. Built originally for the Physics Division's weapons physics applications, the transition plan for this beamline was initiated in 1996 and completed in early 1998. To support this dedicated facility, we established an NSLS Participating Research Team consisting of the Los Alamos Integrated Structural Biology Resource, the National Research Council of Canada Biotechnology Research Institute, the Department of Energy (DOE) Molecular Biology Institute at the University of California at Los Angeles, the Brookhaven Biology Department, and the Pharmaceutical Division of Hoffman-La Roche, Inc. The primary emphasis at X8-C will be on solving novel protein structures through use of multiwavelength anomalous dispersion (MAD) on small crystals (100 µm and less) under cryogenic conditions (Fig. 2). X8-C is well-suited for this type of experiment because it has optics that deliver a high flux with low bandwidth when compared with other protein-crystallography beam lines at the NSLS.

Over the last year, the structural genome initiative (a systematic approach to obtaining the structures of large numbers of biologically and medically important proteins) has lead to the beginnings of a large-scale national effort with support from the DOE Office of Biological and Environmental Research and the National Institute of Health (NIH). Our goal is to maintain leadership in this area, which we expect to be both an important scientific issue in structural biology and a critical component of future biotechnology (there is already significant interest by major pharmaceutical companies). We were co-organizers of a national workshop entitled "Structural Genomics" which was held at Argonne National Laboratory in January 1998. The meeting was attended by internationally prominent figures in structural biology and genomics, as well as by representatives from the offices of DOE, NIH, the National Science Foundation, and other sponsors. The workshop produced an enthusiastic consensus that structural genomics will be an important part of the post-genome biological landscape. The meeting was widely reported in the scientific press.[3,4] In collaboration with members of the Life Sciences Division and the UCLA Molecular Biology Institute, we have begun a pilot project in structural genomics including large-scale overexpression, purification, and crystallization of proteins from a thermophilic bacterium. This project is expected to produce approximately 60 novel structures over the next three years, almost all of which will be solved by MAD techniques on beamline X8-C.

Functional Brain Imaging

A recent unpublished NIH position paper states "Brain imaging is one of the most rapidly advancing fields in science today. More than any other area of biology, it is a field in which the progress of research is dependent on improving technologies and computational power. . . [R]apid improvements in brain imaging methods provide our best hope for understanding brain mechanisms that play a role in mental illness and, eventually, for improving our ability to diagnose, treat, and prevent neurologically based brain disorders." P-21's effort in functional brain imaging focuses on the combined use of magnetoencephalography (MEG), anatomical MRI, functional magnetic resonance imaging (fMRI), and optical imaging techniques to develop improved techniques for noninvasive imaging of the human brain. High-resolution MEG arrays and optical imaging techniques are also used to image neural activity directly from the brains of experimental animals (Fig. 3). Together with collaborators at the University of New Mexico School of Medicine, Albuquerque Regional Federal Medical Center in New Mexico, Massachusetts General Hospital in Boston, and the University of Minnesota School of Medicine in Minneapolis, P-21's work in functional brain imaging contributed significantly to the recent formation of the $60M National Foundation for Functional Brain Imaging to be headquartered in Albuquerque.

Members of P-21 are engaged in projects to design improved multichannel magnetic sensors, develop more accurate mathematical models for localizing the electrical and magnetic signals from the brain, validate MEG using known current sources in computational and physical models of the brain, and use MEG to address important questions in basic neuroscience and in research on neurological and psychiatric disorders.

Combining MEG and anatomical MRI with other functional imaging techniques such as fMRI and positron emission tomography (PET) offers the opportunity of increasing the combined spatial and temporal resolution of functional imaging techniques well beyond that of any single method, as noted in the

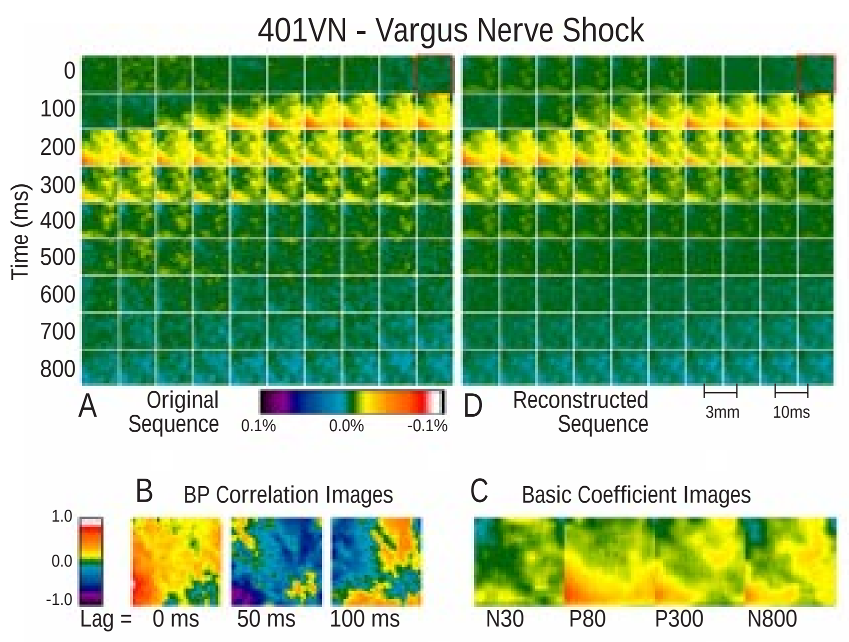


Fig. 3   High-resolution optical imaging techniques allow for images such as this, which accurately measure neural activity directly from the brain.

NIH quotation above. We are engaged in developing mathematical models for combining these alternative forms of brain imaging. This work is part of a nationwide effort to develop three-dimensional (3-D) computational models of the brain in which a variety of structural and functional information can be represented for storage, retrieval, and analysis.

SQUID-Based Sensors and Applications

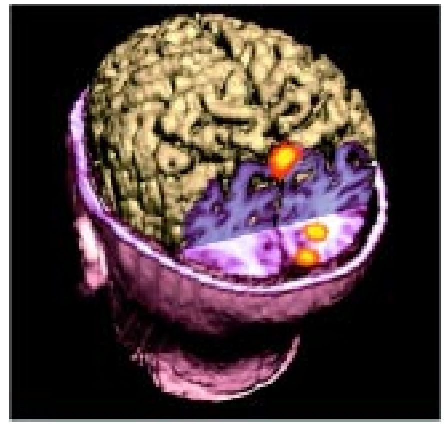
The goals of our MEG SQUID sensor projects are to develop, test, and evaluate sensor systems, numerical techniques, and computational models for functional imaging of the human brain using MEG. MEG involves the use of SQUIDs to measure magnetic fields associated with human-brain activity. Measurement of the magnetic fields of the brain (which are approximately a billion times smaller than Earth's) requires sensitive magnetic sensors, magnetic shielding from the environment (currently implemented through a shielded room), and advanced signal-enhancement and modeling techniques. Because magnetic fields readily penetrate the skull, MEG offers the potential for noninvasive measurement of brain function in much the same way that computed tomography and MRI allow the noninvasive detection of brain structure. MEG has therefore generated considerable interest in its possible use as a tool in basic neuroscience for functional mapping of the human brain, as a clinical tool for the assessment of neurological and psychiatric disorders, as a possible source of signals for use in the development of neural prosthetics and human-machine interfaces, and in other applied contexts.

MEG directly measures a physical effect of neuronal currents with temporal resolution not limited by the sluggish vascular response, unlike PET and fMRI that measure hemodynamic changes associated with neuronal activity. High temporal resolution is particularly important for studying neurological disorders such as epilepsy, where temporal information is a major diagnostic, and for fundamental studies of synchronization and oscillatory brain activity. Our whole-head MEG system is based on the P-21 patented principle of superconducting image-surface gradiometry where magnetic sources are imaged on the surface and magnetometers near the surface sense the combined fields as if the sensors were gradiometers (Fig. 4). Fabrication and assembly of this system are nearly complete. This system will play a major role in the National Foundation for Functional Brain Imaging.

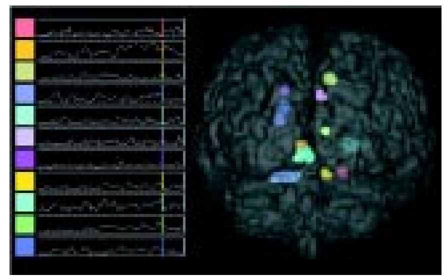
Significant progress has also been made in development of novel, improved approaches to the MEG forward and inverse problems. In the case of the forward problem, the two major existing approaches are spherical (or spherical-shell) models and boundary-element models. Spherical models have the advantage of computational simplicity but they can result in significant inaccuracies in regions of the head that depart from spherical geometry. In contrast, boundary-element models are more accurate, but at a significant increase in computational complexity. Working with our collaborators, we have developed an alternative to the spherical and boundary-element approaches to the forward problem, termed the weighted multi-sphere approach because it uses multiple spheres fit to the local curvature of the skull. This approach can achieve accuracies approaching those of the boundary-element model with computation time comparable to that of the simple spherical model. With respect to the inverse problem, members of P-21 recently demonstrated a new probabilistic approach based on Bayesian inference, which is described in detail in a research highlight in Chapter 2 of this report. Unlike all other approaches to the inverse problem, this approach does not result in a single “best” solution to the problem. Rather, it estimates a probability distribution of solutions upon which all subsequent inferences are based. This distribution provides a means of identifying and estimating the features of current sources from surface measurements that are most probable among the multiple solutions and can account for any set of surface MEG measurements. The promise of this approach has been demonstrated using computer simulations and experimental data. In particular, we have demonstrated for the first time that information can be extracted not only about the locations of regions of activity but also their extent.

In addition to applications of SQUIDs to MEG and related biological applications, members of P-21 have made significant accomplishments in applying these same sensors to the nondestructive evaluation of nuclear weapons components and materials. As described in detail in a research highlight in Chapter 2 of this report, a SQUID microscope has been designed, built, and tested for applications in the Enhanced Surveillance Program. This system uses a SQUID cooled by liquid nitrogen to map magnetic fields produced by eddy currents in a sample at room temperature. Material defects in the sample (due, for example, to cracks, seams, stress fractures, corrosion, or separation of layers) perturb eddy currents and produce magnetic field anomalies when compared to uniform, defect-free materials. Such anomalies can be detected even if the material defects are located below the surface in deeper layers of the sample. This latter capability is particularly important for nondestructive evaluation of weapons components and materials.

In the first full year of the project, the SQUID microscope team designed, fabricated, and performed successful initial tests of a SQUID microscope based on high-critical-temperature SQUID sensors. This work won P-21’s SQUID Microscope Team a Los Alamos Distinguished Performance Award for 1998. Their success was based in part on their ability to exploit P-21’s extensive experience in applications of SQUID sensors for noninvasive measurement of human brain function. Given this successful proof of concept, the team is now refining the SQUID microscope design to improve its sensitivity and resolution, to permit operation in magnetically noisy environments, and to use higher-frequency induction fields.



a)



b)

Fig. 4 In our whole head MEG system (shown in Fig. 1), the locations and time courses of active neural populations are calculated using computer models (a) and displayed on MRI images of brain anatomy (b).

Biologically Inspired Hardware, Computation, and Robotics

P-21 is currently making a significant effort in the study of adaptive systems focused on the development of autonomous or semi-autonomous machines, and there is an opportunity for this effort to become much larger. One focus of this work is the performance of simple mobile machines designed primarily to survive in their intended environment. Such devices are controlled by unique analog neural circuits, are often solar powered, and are capable of surprisingly complex behavior, and they may achieve enhanced utility through collective behavior. A second focus concerns the development of more capable robot legs modeled on the legs of insects. The aim is to develop legs that closely integrate the materials, sensors, actuators, power systems, and control structures as much as possible in the way that these components are integrated in the structure of animals. This work is the first step in the development of complex, agile walking robots. It is multi-disciplinary by nature, requiring the participation of materials scientists (for structure, energy systems, and actuators), mechanical and electrical engineers, bioscientists, physicists, and others. Opportunities exist for P-21 to become a major Laboratory and national resource in adaptive hardware, computation, and robotics for national security missions of the DOE Office of Nonproliferation and National Security, the intelligence community, and the Department of Defense (DOD) Advanced Research Projects Agency (DARPA). An expanded effort in this direction would exploit our existing strengths in robotics, engineering, neuroscience, and computation, and would significantly expand our contribution to core Laboratory missions with first-rate science and technology.

A major focus of such an expanded effort will be adaptive and biologically-inspired computation. Millions of years of evolution have endowed organisms with the ability to solve problems that overwhelm even the largest of today’s DOE Defense Program stockpile stewardship computers. Biological solutions to these seemingly intractable computational problems involve massively parallel, richly interconnected networks of neurons whose collective activity is essential to their function. Artificial neural networks (ANNs), cellular automata, and other approaches to adaptive computation have achieved considerable notoriety as potential solutions to difficult computational problems because of their similarities to biological neural networks and because, unlike conventional numerical simulations, they do not require a detailed algorithmic solution to the problem a priori. Instead, because of their inherent plasticity and their ability to “learn” from experience, ANNs can be “trained” to solve problems in ways that are not explicit in their initial architecture.

ANNs are ultimately limited, however, because of their inherently rudimentary representation of the computational capabilities of real neurons. In actual neurons, tree-like dendritic structures are the site of a complex analog computation involving the timing of input spikes, the rapid interplay of voltage- and ion-specific membrane channels, and the active feedback of signals from the cell body back into the dendritic tree.[5] The size of ANNs to date is generally very small on the biological scale, where even the simplest of organisms have networks of hundreds of neurons, and most have vastly more. We believe that it is possible and desirable to begin to design neural networks that are more closely linked to biological neural systems, to use them to address hitherto intractable computational problems that biology appears to have solved in an elegant fashion, and ultimately to use systems of such realistic neurons to build useful devices.

Single Molecule Spectroscopy and Electrophoresis

P-21 and its collaborators have extended their work on the detection and characterization of single molecules in a liquid. The goal of this research is to measure and characterize the spectroscopic properties of individual molecules (Fig. 5). Such spectroscopic measurements can be used to identify the presence of a particular molecular species in an extremely dilute solution, or they can be used to probe the local environment that surrounds an individual molecule. The former capability promises a new level of speed and sensitivity for medical diagnostics, whereas the latter capability makes it possible to study properties of biological systems that cannot be measured when a lack of sensitivity confines measurements to the determination of the average properties of a large ensemble of microenvironments. Thus far, the spectroscopic properties measured at the single-molecule level include emission spectra, fluorescence lifetime, and total emission intensity. Recently the single-molecule spectroscopic approach has been extended to include single-molecule electrophoresis and approaches to ultrasensitive detection of viral and bacterial pathogens in soil and water samples. We are exploring additional applications for basic research and for medical diagnostics.

High-Speed Electronics Team

Already a diverse group, P-21 became more diverse and significantly stronger with the addition in December 1997 of the electronics team formerly in P-22. Previously a key element of the nuclear test program at the Nevada Test Site (NTS), the electronics team refocused its efforts to other defense and civilian needs with the cessation of nuclear testing. We now, quite literally, have the capability within P-21 to take an idea from the “gleam-in-the-eye” stage, through basic and applied research, to a fully developed, fieldable instrument for direct use by sponsors or industrial partners. The electronics team brings substantial capabilities in electronics design, fabrication, and implementation to P-21 that are of great value in their own right and have significant potential for the enhancement of our biological programs. In less than one year, the electronics team has made contributions in all of the focus areas listed above, including exploration of detectors derived from remote

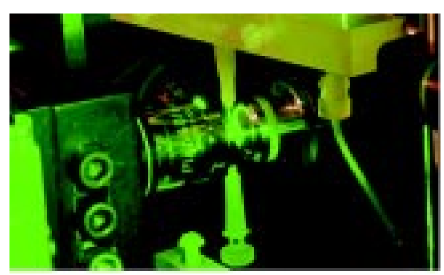


***Fig. 5** The single-molecule electrophoretic analyzer detects single labeled molecules in solution.*

ultra-low light imaging (RULLI) techniques (see the research highlight on this topic in Chapter 2) for applications in biomedical imaging and single molecule detection, contributions to high-throughput protein purification for the structural genome project, and other areas.

In collaboration with the Life Sciences Cytometry Group (LS-5), the P-21 Electronics Team played a key role in the development of a flow cytometer to be used as part of a suite of instruments by the U.S. Army Chemical and Biological Defense Command. The instrument provides point detection of a biological warfare attack at a forward battlefield location, and rapid identification of the biological warfare agent. The requirements called for the instrument to be exceptionally compact, rugged, and easy to use while precisely identifying a host of bio-agents. The miniature flow cytometer (MiniFCM) successfully completed field tests in September 1998, and 14 instruments are currently in use at Fort Polk, Louisiana.

The electronics team significantly increased the dynamic range of the instrument while also reducing the size of the required electronics (Fig. 6). A unique scheme of data acquisition, which used two ADC’s and overlapped their coverage, was used to increase the dynamic range to 16 bits with very low noise. Simultaneously detecting particles in very low channels and high channels was fundamental to the use of the instrument (Fig. 7). In addition, the size of the MiniFCM was reduced by designing acquisition electronics around a multichip module hybrid, which placed 32 integrated circuits on a 30 × 55-mm substrate. The team also simplified the controls and user interface of the instrument, transforming a clinical instrument controlled by a separate PC and software into a field instrument controlled by five buttons.

***Fig. 6** The miniFCM can detect specific bio-aerosols, cells, and spores within 120 seconds. It is self-contained and easily portable, weighing only 60 lbs and measuring 2.5 ft^3.*

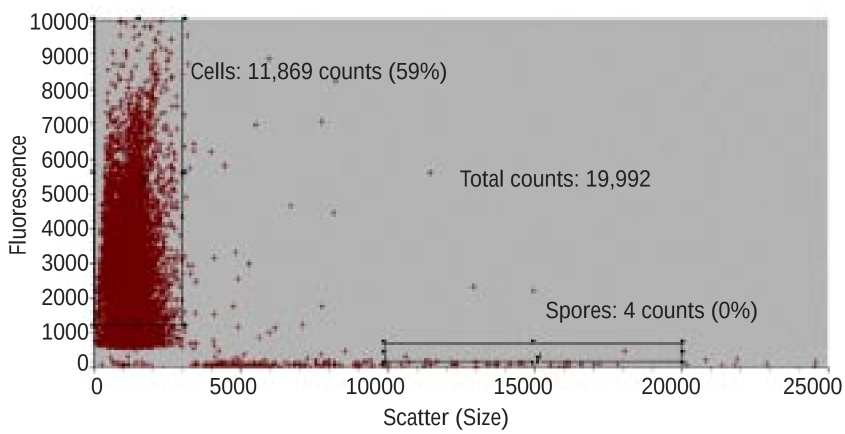


***Fig. 7** Bivariate dot plot of size (scatter) versus DNA fluorescence for particles detected during a field trial of the miniFCM at Dugway Proving Ground.* Erwinia herbicola*, a vegetative cell that causes black spots on pears, was released outdoors. The miniFCM was able to detect both the cells (upper left) and spores (lower right) of this pathogen simultaneously, even though the spores are larger and less fluorescent.*

The instrument is part of a mobile bio-agent laboratory. It consists of a precisely aligned and focused optical platform, a fluidic system for sample delivery and system decontamination, and a virtual memory extension (VME)-based data acquisition and control system. Unlike commercial flow cytometers, these systems had to be made physically rugged to survive transportation and be immediately on-line for bio-agent detection. This required extremely stabile optical and fluidic components and special detail in every aspect of instrument construction. The result is a remarkably high level of adjustment-free operation, especially when compared to standard commercial instruments.

Further Information

For further information on all of P-21's projects, refer to the project descriptions in Chapter 3 of this progress report. Some of our major achievements are also covered as research highlights in Chapter 2, as mentioned above. These include SQUID microscope development, research on Bayesian methods for addressing the MEG inverse problem, development of RULLI techniques, and the structural genome project.

References

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P-22: Hydrodynamic and X-Ray Physics

Joseph S. Ladish,
Group Leader

Jack Shlachter,
Deputy Group Leader

Introduction

The mission of the Hydrodynamics and X-Ray Physics Group (P-22) is to solve challenging experimental physics problems relevant to our national security, aiming to reduce the threat of war by helping to ensure the reliability of our nuclear-weapons stockpile and by limiting the proliferation of weapons of mass destruction. Our experiments focus on the hydrodynamic properties of materials as they undergo explosive and implosive forces. For nuclear weapons and other highly dynamic systems, knowledge of material behavior under extreme physical conditions is important for developing computational models. Our x-ray capability is predominantly involved in the diagnosis of dynamic material behavior.

To fulfill its mission, P-22 maintains and develops a creative multidisciplinary team, broad physics and engineering capabilities, and state-of-the-art technologies. Experimental efforts in P-22 cover a wide range of physics disciplines, including hydrodynamics, x-ray spectroscopy and imaging, plasma physics, radiation hydrodynamics, optics and fiber optics, microwaves, electromagnetics, atmospheric physics, and atomic physics. In support of these experiments, P-22 has expertise in a variety of engineering disciplines, including analog and digital electronics; electro-optics instrument design and fabrication; high-voltage, low-inductance pulsed-power engineering; and fast-transient data recording. P-22 is also the home of the Pegasus II Pulsed-Power Facility (Fig. 1) and of the future Atlas High-Energy Pulsed-Power Facility (Fig. 2). These high-energy experimental facilities provide a valuable laboratory test bed for the investigation of dynamic material properties.

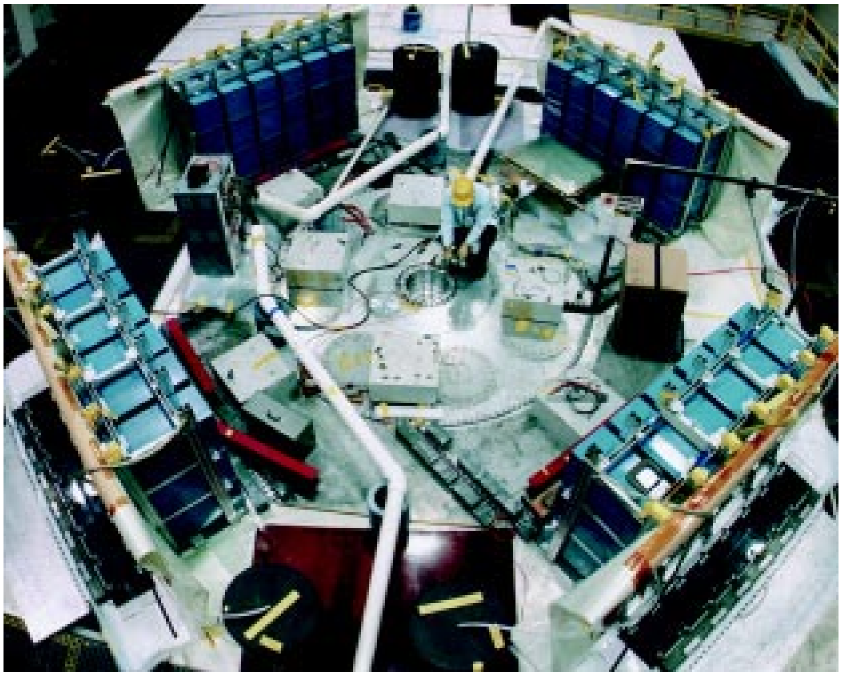


***Fig. 1** View of the upper half of Pegasus II. The facility consists of 144 energy-storage capacitors arranged as a two-stage Marx bank with a maximum erect voltage of 100 kV.*

Fig. 2 The Atlas capacitor bank will be housed in 12 oil tanks that are arranged around a centrally located target chamber. Each oil tank will contain up to two removable maintenance units and up to 32 capacitors.

The mainstay of P-22 has traditionally been its support of the nuclear-weapons program. P-22 continues this tradition by supporting science-based stockpile stewardship (SBSS), which is the foundation of the present Los Alamos nuclear-weapons program. SBSS requires the development of complex experiments on diverse facilities to address the relevant physics issues of the enduring stockpile. In P-22, we support SBSS by applying the scientific and engineering expertise that we developed for the nuclear test program to investigate and understand primary and secondary weapons-physics issues that are crucial in a world without nuclear testing.

Nevada Test Site

P-22 is deeply involved in protecting and archiving the volatile test data it took during more than three decades of underground nuclear testing at the Nevada Test Site (NTS). Our goal is to bring the group's data to a stable and readily accessible state. These data will be used to benchmark all future calculational tools. The archiving activities constitute a significant effort in P-22 and involve individuals responsible for the original execution of underground nuclear tests as well as trainees. Many of the numerical algorithms developed for analyzing the information from underground tests have been ported to modern computer platforms as part of our effort to preserve this valuable and unique data.

In addition, P-22 continues to participate in experiments performed underground at NTS, both to maintain our readiness to support a resumption of nuclear testing should the need arise, and to study the physics of weapons performance and materials (Fig. 3). These experiments increase our understanding of weapons science by allowing improvements in code calculations and in estimates of the severity of problems and changes occurring in the nuclear stockpile as it ages.

Fig. 3 P-22 data recording trailer at the NTS U1A underground test facility. The trailer uses modern fiber-optic systems and state-of-the-art digitizers and timing systems to gather and record data from explosive experiments located almost 1,000 ft below ground.

At present, we are supporting the Los Alamos Dynamic Experimentation (DX) Division on experiments to measure the properties of material ejected from shocked plutonium. These experimental efforts are discussed in detail in a research highlight in Chapter 2. By performing these experiments underground at NTS, the plutonium is handled and contained in a manner similar to that used for underground nuclear tests, maintaining the readiness training necessary to support the potential for future nuclear tests.

Above-Ground Experiments

In support of the Weapons Program's above-ground experiments (AGEX-1), we have been developing diagnostics to study the physics of high-pressure shock waves. Among the diagnostics currently under development are

- visible-wavelength and infrared pyrometers to determine the temperature history of the back surface of a shocked material under conditions where this surface either releases into free space or is tamped by an anvil,
- low-energy x-ray sources for imaging of shock-produced low-density material (ejecta), and
- a technique for measuring the speed at which moving, high-density material can produce a fiber-optic signal.

We anticipate development of several other techniques to study material phases, including

- a very-short-pulsed laser and an ultrafast streak camera to determine by either second harmonic generation or reflectivity whether the surface of a shocked sample has melted, and
- an x-ray diffraction technique to measure phase changes at the surface of a shocked sample.

These diagnostics will be used to study shocks produced by explosives, flyer plates, gas guns, and the Pegasus capacitor bank.

In other AGEX-1 work, we are supporting the development of the Dual-Axis Radiographic Hydrotest Facility (DARHT) by studying the beam physics of DARHT's prototype, the Integrated Test Stand (ITS). We have built and successfully fielded a magnetic spectrometer to measure the beam energy as a function of time in the 70-ns ITS pulse. In addition, we are developing a microwave interferometry diagnostic to nonintrusively measure the beam electron density and properties of the expanding target plasma created in the interaction of the electron beam and bremsstrahlung converter. We are also participating in the development of new nonintrusive beam diagnostics for the 2-μs injector of the DARHT second axis.

High Energy Density Physics

The High Energy Density Physics (HEDP) program has been conducting experiments of interest to the weapons community at the 4.6-MJ Pegasus II Pulsed-Power Facility, which can be used as a radiation driver or as a hydrodynamic driver in convergent geometry (Fig. 4). Experiments are being performed to investigate a wide range of phenomena, including nonsymmetrical hydrodynamic flow, the behavior of materials undergoing large strains at high strain-rates, frictional forces at interfaces with differential velocities on the order of kilometers per second, instability growth at interfaces in materials with and without material strength, and ejecta formation of shocked surfaces. In addition, we are pursuing pulsed-power research on liner stability, current joints, and power-flow channels to ensure optimal performance for the future Atlas facility and for advanced, high-current, explosive pulsed-power systems. P-22 has already provided pulsed-power and diagnostic expertise to Procyon, Ranchito, and Ranchero, the Laboratory's existing high-explosive pulsed-power systems.

P-22 is the future home of Atlas, the next-generation 23-MJ pulsed-power facility. Atlas will provide advanced equation-of-state (EOS), material property, and hydrodynamic capabilities for weapons-physics and basic research. 1996 marked the official start of the Atlas construction project, with the first dollars arriving for detailed facility design. A major milestone in the project, approval of the DOE critical decision (CD-3) that authorized the start of construction, was reached during 1998. Research and development (R&D) activities since 1996 have been centered on component development, prototype design and testing, and preliminary design of Atlas experiments that will provide an understanding of the scaling of physical phenomena from present data to higher energies. Physics issues of interest are material properties at high strains and strain rates, EOS measurements at high pressures, hydrodynamic response and EOS of strongly coupled plasmas, and interface physics. The Pegasus and Atlas facilities and the current and anticipated research activities are described in detail in a research highlight in Chapter 2 of this progress report.

In another part of the HEDP program, P-22's plasma-physics expertise and ability to do large-scale integrated experiments have provided group members with the opportunity to participate in several collaborations with the premier All-Russian Institute of Experimental Physics at Arzamas-16 (VNIIEF), the weapons-design laboratory that is the Russian counterpart to Los Alamos. In addition to giving us the chance to learn about some of the Russians' unique capabilities, the collaborations provide Russian weapons designers with an opportunity to do peaceful basic scientific research and to integrate themselves into the world's broader scientific community. These collaborations are based on our mutual interests in high-explosive-driven pulsed power, wherein the Russians have clearly demonstrated scalability to large systems that is unmatched to date in the United States. P-22 is

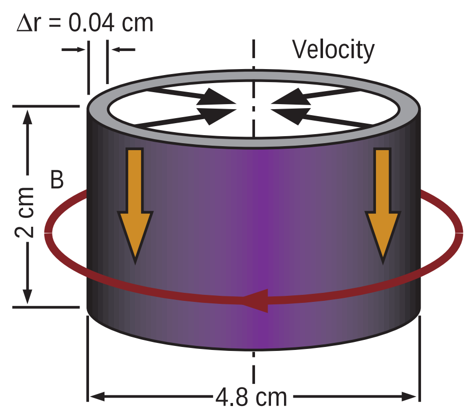


***Fig. 4** Recent research at Pegasus II has focused on hydrodynamic experiments using a standardized solid, cylindrical drive liner. Pulsed electrical currents create a strong magnetic field (B) and high current density around the liner. The interaction of the current and magnetic field produces forces that implode the liner.*

participating in several major collaborative efforts, including experiments on the Russian MAGO system, a possible candidate for magnetized target fusion; attempts to convert a frozen rare gas to a metal by compressing it in a large magnetic field; the design and testing of a thin, imploding cylinder for a megajoule x-ray source; and studies of the properties of materials at cryogenic temperatures in magnetic fields up to 1,000 T.

We are continuing to perform integrated and fundamental radiation hydrodynamic experiments using laser- and z-pinch-driven radiation sources at the Nova and Z facilities at Lawrence Livermore National Laboratory and Sandia National Laboratory, respectively (Fig. 5). We have developed diagnostics for measuring radiation flow, including x-radiography, VISAR, gated x-ray imagers, filtered x-ray diodes, a curved-crystal spectrometer for stimulated fluorescence spectroscopy, and both active and passive shock breakout techniques. Our investigations have examined integrated experiments to understand radiation flow and to evaluate the usefulness of dynamic hohlraum radiation sources for a variety of future applications.

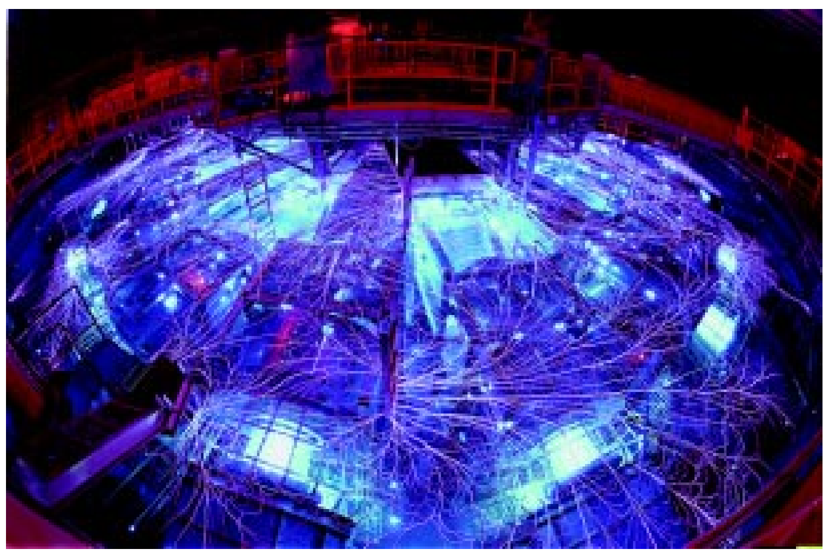


Fig. 5 ***The Z machine photographed as it is firing. Recent radiation experiments on the Z machine have set records for machine performance and provided a basis for weapons physics experiments in support of science-based stockpile stewardship.***

Future Directions

We anticipate a lot of exciting developments in the coming years. As the future operators of the Atlas facility, scheduled to come on-line in 2001, we will continue to support facility development and prepare for future research by testing our experimental designs and calculations at Pegasus and other facilities. In addition, we will focus on diagnostic development to support upcoming experiments at NTS and other AGEX-1 facilities. For further information on all of P-22's projects, refer to the project descriptions in Chapter 3. Some of our major achievements are also covered as research highlights in Chapter 2. These include experiments at the Pegasus facility and development of the Atlas facility, as well as our recent experimental collaborations at NTS.

P-23: Neutron Science and Technology

Mary Hockaday,
Group Leader

Susan Seestrom,
Deputy Group Leader

Introduction

The Neutron Science and Technology Group (P-23) carries out a synergistic program of basic and applied research in weapons physics, nuclear physics, and quantum information science. The common feature of this diverse set of efforts is the application of state-of-the-art techniques in particle and light detection and the recording of transient events.

Within the area of weapons physics, we participate in design and fielding of subcritical experiments, non-nuclear hydrodynamic experiments in support of above-ground experiments (AGEX-I), pulsed-power experiments, and archiving and analyzing data from past nuclear-weapons tests. Our fundamental research focuses on nuclear and weak-interaction physics and on astrophysical phenomena involving the detection of solar neutrinos and ultra-high-energy gamma rays. Applied research includes the development of quantum-information technologies, such as quantum computation and encryption (involving single-photon detection) and the application of imaging and neutron technologies to problems relevant to national defense or industry.

We conduct our research at local facilities such as the Los Alamos Neutron Scattering Center (LANSCE), Pegasus, Milagro (Fig. 1), and local firing sites, as well as at remote facilities like the Nevada Test Site (NTS) and the Sudbury Neutrino Observatory (SNO). All of these facilities are world class, offering the best available resources for our research. Of these facilities, only the Milagro

Fig. 1 The Milagro detector is comprised of 723 photomultiplier tubes situated in a 5,000-m^2, 8-m-deep pond at an altitude of 8,700 ft. The photograph shows the pond before it has been filled with water, which will allow the Kevlar-bound photomultiplier tubes to extend towards the sky. Milagro should be able to detect the particle showers produced by very high-energy gamma rays as they enter the atmosphere.

gamma ray observatory is owned and operated by P-23. We contribute to Laboratory programs in science-based stockpile stewardship (SBSS), accelerator production of tritium (APT), and energy research, as described below.

Weapons Physics and Science-Based Stockpile Stewardship

With the end of nuclear testing, SBSS has become the foundation of the Los Alamos nuclear-weapons program. Our knowledge of how complete nuclear weapon systems perform relies on data obtained from tests at NTS and test locations in the Pacific Ocean. Saving, analyzing, and documenting NTS weapons test data is crucial to the success of SBSS. P-23 shares responsibility for preservation and analysis of these data with other groups involved in these tests. In P-23, physicists and engineers who performed the original measurements are working to analyze and correlate the data of different events. In addition, new scientists are learning the technologies of making such measurements in case the need should arise for future underground tests.

The work of the group concentrates on analysis of pinhole neutron experiments (PINEX) imaging data and on neutron emission measurements (NUEX and THREX). These data complement the reaction history and radiochemical measurements made by other groups. As a whole, this research has provided a better understanding of the underlying physical processes that generated the data, and the comparison of results from different tests has allowed us to study systematically the behavior of nuclear explosives.

To ensure the success of SBSS in allowing us to certify the performance of our nuclear weapons in the absence of nuclear testing, P-23 is striving to develop better physics models that can be incorporated into computer codes to calculate explosive performance. Only by validating such codes with the existing NTS data will we be able to address with confidence the issues of aging and remanufacture of our stockpile weapons.

In addition to the analysis of NTS data, P-23 is participating in a series of experiments to explore weapons-physics issues of a more microscopic nature. In these experiments, we use chemical explosives and pulsed-power machines such as Pegasus to examine issues such as the EOS of shocked materials, formation and transport of ejecta from shocked surfaces, and growth of hydrodynamic instabilities. Our work includes a series of underground experiments involving plutonium at the U1a facility at NTS. These experiments employ a wide range of technologies, including gated visible imaging, gated x-ray imaging, holography, and infrared temperature measurement, to explore the physical phenomena. P-23 is currently developing fast infrared imaging technology, which will provide the ability to study freeze-frame dynamic motion in the infrared range. The data from all of these technologies allow us to better understand hydrodynamics of interest to the weapons program. As computer models are developed further, the data will allow us to benchmark the models.

Other weapons program work focuses on what happens to a weapon as its components age. NTS experiments and other previous weapons tests did not focus on this issue, and the data from these tests are not sufficient to assure the safety and reliability of the nuclear-weapons stockpile without nuclear testing. The SBSS program is intended to provide a scientific basis for addressing this and other assurance issues without nuclear testing. As part of this effort we have joined colleagues in other groups and divisions at Los Alamos National Laboratory, as well as from the Lawrence Livermore National Laboratory, to study the following issues:

- the performance of chemical explosives, including changes in performance as they age;
- the fundamental physics of plutonium, *e.g.*, the phonon spectrum;
- the temperature of materials undergoing hydrodynamic instabilities; and
- nuclear cross sections that are required for better analysis of radiochemical data from previous weapons tests.

For these studies we use neutrons from LANSCE sources, including moderated neutrons from the Manual Lujan, Jr., Neutron Scattering Center (MLNSC), moderated neutrons with tailored time-structure from the Weapons Neutron Research (WNR) Blue Room, and unmoderated neutrons from the WNR fast-neutron source. Neutron spectroscopy by time-of-flight techniques is central to all of these projects.

An important element of the SBSS program at LANSCE is hadron radiography. P-23 is supporting this effort with a cold-neutron radiography project at the MLNSC and by participation in the proton-radiography project. P-23 developed a cooled, charge-coupled device (CCD) imaging system with fast gating and image intensification for use in hadron radiography. The system was first applied to radiograph a low-density material encapsulated in a high-density casing using neutrons produced at the WNR in the 5- to 200-MeV energy range. The group has also collaborated with the Subatomic Physics Group (P-25) in the development of a pixellated, gas-amplification wire-chamber detector for hadron radiography. Our future work includes development of framing camera techniques to be applied to proton radiography. We propose to include a framing camera between the image intensifier and the CCD camera. This will enable the recording of four frames on each CCD and would increase the total number of frames to 28.

P-23 also supports the SBSS program by obtaining nuclear data at the WNR facility. At WNR, a large array of Compton-suppressed germanium detectors, known collectively as the GEANIE detector, is used to measure gamma rays from neutron-induced reactions. Our interests at present are in the ^{239}Pu(n,2n)^{238}Pu cross section, where different nuclear-reaction models give markedly different predictions, and in the nuclear structure area of "complete spectroscopy," where models of nuclear-structure symmetries and the transition from order to chaos in nuclear spectroscopy can be tested.

A critical, and currently limiting, component to a number of weapons program experiments is the need for better imaging technologies. Prior to the cessation of underground testing at NTS, the Laboratory (previously in J-12 and P-15, and then in P-23) developed an in-house capability to meet the advanced imaging needs for the Weapons Program's underground shots. Currently, the SBSS program has turned to above-ground experiments that are again placing ever increasing demands on imaging and other technologies. There is currently a need for an imaging sensor that can be gated (or shuttered) in the few-nanosecond to subnanosecond regime, can achieve a high frame (or data) transfer rate (up to 10^7 frames per second), has a high quantum efficiency (1% to 50%) and sensitivity (<10 photons per pixel detection), and covers the spectrum from visible light into the near-infrared regime (380 nm to 5 μm in wavelength). Such advanced imaging capability is not available commercially, and the technology for achieving such imaging is presently state-of-the-art or in development.

Accelerator Production of Tritium

P-23 contributes to the APT program by supplying basic nuclear-physics data, performing integral tests of the calculated neutronic performance of benchmark systems, developing beam diagnostics, and participating in irradiation studies of components for this program. Basic nuclear physics data include neutron total and reaction cross sections and activation data, mostly measured with the spallation neutron source at WNR. Integral tests employ small-scale mockups of the accelerator target and the neutron-reflecting blanket. These allow the initial neutron production, the final tritium production, and intermediate steps to be quantified and compared with calculations. Beam diagnostics use P-23's imaging capabilities. These data-measurement activities and integral demonstrations are continuing as the APT program progresses.

Nuclear Research

Compound nuclear states provide an excellent laboratory for studying violation of basic symmetries because of enhancements of the effect of parity violation in this system that are of order 10^7. The origin of these enhancements is a combination high-level

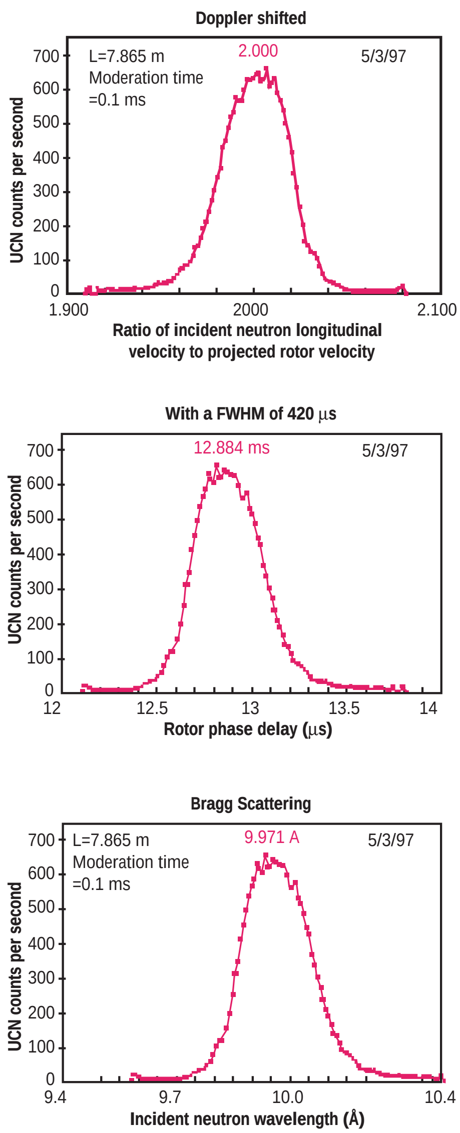


Fig. 2 Conditions and results for the UCN rotor reflector experiments. Thirty UCN per pulse were detected when the rotor was within 90 µs of the center. Slow neutrons generated with the rotor reflector system will be used to investigate the radioactive decay of free neutrons.

density and large difference between *s*-wave and *p*-wave neutron widths. This width difference enhances the effects of parity violation because we observe mixing of large *s*-wave resonances into small *p*-wave resonances. In the past we have observed parity violation in neutron resonance reactions for a large number of resonances in more than a dozen target isotopes. With techniques developed by P-23 and our partners, we identified very weak p-wave resonances where parity violation can occur and be observed with amplitudes of up to 10% of parity-conserving interactions. Nuclear theory predicted that the sign of the parity-violating effect should be random, and for all but one nucleus it appears to be. The exception is thorium-232 (^{232}Th), where the violation for the eight resonances with the strongest effects are all of the same sign, which would have a less than 0.25% probability of occurring if the sign were indeed random. We have investigated all of the readily available isotopes at maxima in the p-wave strength function and therefore are bringing this research to a close. The case of ^{232}Th remains an enigma. As a follow-on to our work in parity violation in heavy nuclei, we are developing an experiment to measure parity violation in the *np* system. This experiment will attempt to measure the asymmetry in gamma rays emitted after capture of polarized neutrons by protons in a liquid-hydrogen target. The experiment will be conducted at the MLNSC, and the shuttle, beam guides, and apparatus are currently in design.

We are also active in other tests of fundamental symmetries in the beta decay of trapped atoms and of free neutrons. Sensitive tests of the parity-violating beta-spin asymmetry correlation in the decay of rubidium-82 (^{82}Rb) constitute one experimental sequence that we anticipate will yield results with a precision one order of magnitude greater than any previous experiment (see the detailed research highlight on this topic in Chapter 2). In studies of the decay of the free neutron, we initiated the EMIT (“time” reversed) collaboration to pursue a search for time-reversal invariance violation. For this we have designed an experiment that promises to be seven times more sensitive than previous experiments. We have also proposed an experiment to measure the beta asymmetry in the beta decay of polarized ultracold neutrons (UCN).

UCN were first produced at LANSCE in 1996 by the use of a rotor reflector (Fig. 2). These neutrons travel with speeds of less than 8 m/s. We are continuing to develop this source with improved cold moderators and better rotor reflectors. We plan to use this source to test the key concepts in an experiment to measure the radioactive decay of free neutrons. We are also doing research and development aimed at an experiment to measure the neutron electric dipole moment using UCN produced and stored in a bath of superfluid ^{4}He. Both of these measurements aim at detecting physics beyond the standard model of strong and electroweak interactions. We are also studying the feasibility of a cryogenic source of UCN to be operated as a stand-alone spallation UCN source. Preliminary indications are that such a source, using only a few percent of the LANSCE proton beam, could provide the world’s most intense source of UCN. Such a world-class source of UCN at LANSCE would open up new opportunities for experiments in fundamental physics and the possibility of novel applications to materials science.

Another area in basic nuclear research is the Milagro project (see Fig. 1). Very high-energy gamma rays from the cosmos can be detected when they enter the atmosphere and produce an air shower of particles. The Milagro project, located in the Jemez Mountains above Los Alamos, involves the construction and operation of a high-efficiency observatory for gamma rays in the energy range around 10^{14} eV. This observatory is a joint project of Los Alamos and a large number of universities. It will be especially well-suited for the study of episodic or transient gamma-ray sources—that is, for recording gamma-ray bursts. It is operational 24 hours a day, 365 days a year, and its field of view is nearly half of the sky. A small scale version of Milagro, Milagrito, operated in 1998. The full-scale detector is presently being assembled.

We are also involved in ongoing research of solar neutrinos. The number and spectrum of neutrinos from the sun continues to challenge our understanding of solar physics and neutrino properties. For many years we have been working with scientists from the (former) Soviet Union to detect neutrinos by using large quantities of gallium far underground in the Caucasus Mountains. This lengthy study, known as the SAGE (Soviet-American Gallium Experiment) collaboration, has revealed that the number of neutrinos detected is about half of that predicted by the best solar and neutrino models. Now we are collaborating in the development of SNO, a neutrino observatory more than a mile underground in Sudbury, Ontario. The SNO detector will soon be operational and consists of an acrylic vessel holding 1,000 tonnes of heavy water surrounded by another vessel with 8,000 tonnes of light (regular) water. All three flavors of neutrinos (electron, muon, and tau) will be detected. Development of this detector includes the design and fabrication of very-low-background ^{3}He detectors and new electronics. As a spin-off, the very sensitive, low-background detectors developed for the observatory will be used to screen high-density microelectronics for trace radioactive contaminants that can cause computer errors by “flipping” bit patterns. The physical structure has been completed, and the vessel is being filled with water. The first ^{3}He detectors have been tested underground at Sudbury, and they perform as expected. We expect to complete construction and have all counters underground by summer 1999.

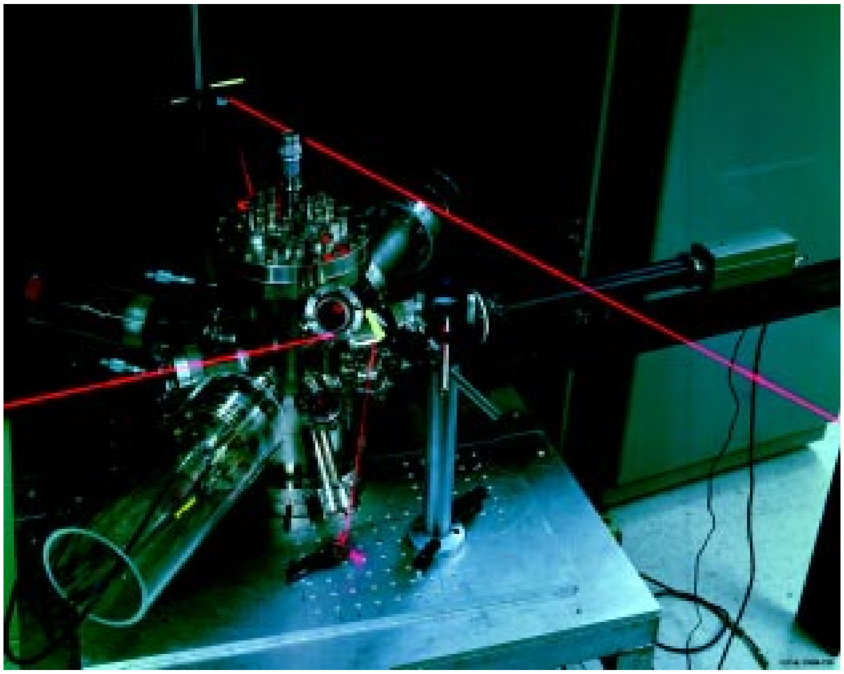
Applications of Basic Research

Quantum computation, a field in its infancy, promises a new approach to solving some problems (regarded as intractable in classical computation) by using the quantum-mechanical superposition of many states (numbers) at once. To realize such a computer, we are developing a system with cold, trapped atoms that represent the quantum-mechanical states. Quantum logical operations are performed with laser manipulations of the states of the trapped atoms (Fig. 3). Using conventional lasers, we have recently succeeded in trapping and imaging calcium ions that have the required spectroscopic structure to allow them to serve as basic quantum-mechanical bits. We are developing advanced diode lasers to perform the same operation, but with much reduced power requirements and cost.

Our applied research also includes work in quantum cryptography, which is covered in a detailed research highlight in Chapter 2. Quantum mechanics provides an approach to unbreakable cryptographic codes that not only can transmit the code "key" with security but that can also reveal the presence of eavesdropping. We have demonstrated this quantum cryptography over 48 km of fiber-optic cable and are developing longer transmission demonstrations. In a related effort, we have demonstrated transmission of a "key" through 200 m of air, and through this technology we are aiming at establishing secure communications between ground-based stations and low-Earth-orbit satellites.

We are also carrying out fundamental studies in "interaction-free measurements." Using the complementary wave- and particle-like nature of light, it is possible to determine the presence of an object without any photons being absorbed or scattered by it. Based on

Fig. 3 Apparatus for manipulating the states of cold, trapped atoms. Using such a system, we have succeeded in trapping and imaging calcium ions that have the required spectroscopic structure to allow them to serve as basic quantum-mechanical bits for quantum computation.



these studies, we have begun investigating the practical implementation of “interaction-free imaging,” where the techniques are used to take a pixellated image of an object, again with the goal of negligible absorption or scattering; at present, a resolution of better than 10 μm has been achieved, and we hope to reduce this even further. This work is covered in a detailed research highlight in Chapter 2.

We also support DOD programs in mine detection and seeker applications. For the detection of land mines, we are investigating the use of neutrons as an interrogating probe, with the detection of the resulting activation gamma rays as the positive signature. High-intensity neutron sources are necessary for the required sensitivity, and we are developing them in collaboration with other groups. Accelerator sources are strongly preferred because their energy can be tuned and specified, and they can be turned off when not in use. We are assessing the required sensitivity of detection, using our extensive experience acquired in developing neutron detectors for the Nuclear Test Program and for accelerator-based experiments. P-23 has also developed a laser-based, range-gated imaging system for the airborne detection of submerged mines. The system has undergone testing in both controlled-tank and open-sea environments. We have supported seeker (target identification) programs with range-gated laser distancing and ranging (LADAR) experiments carried out at the Wright Laboratory’s laser range at Eglin Air Force Base. These experiments are part of a joint DOE/DOD technology-development program.

Further Information

To learn more about the projects described here, as well as other projects within P-23, refer to the project descriptions in Chapter 3. Some of our major achievements are also covered as research highlights in Chapter 2, as mentioned above. These include our work in quantum computation, interaction-free measurement, free-space quantum key distribution, and fundamental symmetries with magnetically trapped ^{82}Rb.

P-24: Plasma Physics

Kurt F. Schoenberg,
Group Leader

Juan C. Fernández,
Deputy Group Leader

Introduction

The Plasma Physics Group (P-24) researches the basic properties of plasmas with a view to applications in important Los Alamos National Laboratory and national programs. Plasmas occur in nature when matter exceeds temperatures of roughly 10,000°C. At these temperatures, the constituent atoms and molecules of matter begin to lose their bound electrons to form a substance composed of positive or negative ions and free electrons. All principal phenomena in plasmas can be traced to the fact that ions and electrons interact with each other through long-range electromagnetic forces. The electromagnetic interactions of groups of charged particles are often coherent, leading to collective modes of plasma behavior. This collective interaction of charged particles, a many-body problem, is the essence of the field of plasma physics.

Roughly 99% of the matter in the universe is in a plasma state. Plasmas can exist over a large range of temperatures and densities. For example, interstellar space contains plasmas with densities of less than one ion or electron per cubic meter at temperatures exceeding 1,000°C. In contrast, plasmas created by intense laser compression of micropellets achieve densities up to 10^{26} ions or electrons per cubic centimeter at temperatures exceeding 10,000,000°C. The understanding and application of such diverse plasmas is a Los Alamos core competency.

P-24 is composed of a diverse technical staff with expertise in plasma physics, plasma chemistry, atomic physics, and laser and optical science. The group uses both on-site and off-site experimental facilities to address problems of national significance in inertial and magnetic fusion, high-energy-density physics, conventional defense, environmental management, and plasma-based advanced or green manufacturing. Our agenda includes basic research in the properties of energetic matter and applied research that supports the principal Laboratory mission of reducing the nuclear danger. The pursuit of this agenda entails the physics of plasmas over a wide and diverse range of conditions, as shown in Fig. 1.

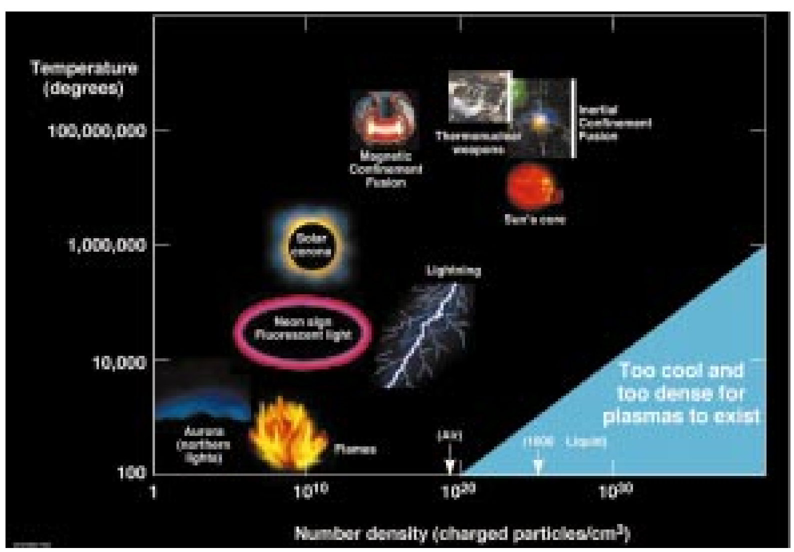


***Fig. 1** As this illustration of the plasma state shows, the physics of plasmas entails a wide and diverse range of conditions.* **(Illustration courtesy of Dr. Don Correll, Lawrence Livermore National Laboratory)**

Atlas

Atlas, a 24-MJ, 30-MA advanced pulsed-power facility scheduled for completion in late 2000, will be capable of imploding 40-g cylindrical liners at velocities of up to 20 km/s on timescales of several microseconds. Such implosions will produce material pressures of several tens of megabars, magnetic fields up to 1,000 T, material strain rates of 10^6 s^{-1}, and highly coupled plasmas of nearly solid densities at temperatures of several electron volts. P-24 is involved in several aspects of the physical design of Atlas, specifically in defining and designing the experimental agenda for the first several years of operation, developing advanced diagnostics to be fielded on these experiments, and fielding experiments on Pegasus and Ranchero to prepare for Atlas operation.

P-24 has responsibility for the design, testing and fabrication of the Atlas power-flow system that transports energy from energy storage capacitors to the load. The power-flow channel is the most difficult component to design because the radial forces on the conductors increase inversely as the square of radius. Thus, significant damage to hardware in the region near the load is expected. As presently envisioned, the power-flow channel will be insulated with solid-dielectric to minimize the relatively large inductance in this region. The conductors will be diskline feeding a conical line connected to the load. The conductors will be held in place during the shot by steel weights placed in contact with both transmission lines.

The Atlas Physics Design Team, which includes P-24 staff, has developed a list of the varieties of experiments to be fielded in the first 200 shots (the first two years of Atlas operation). Included on this list are experiments to investigate Rayleigh-Taylor mix, Bell-Plesset deformation of the liner, friction at high relative velocities, on-hugoniot EOS measurements, calibration of the NTS nuclear impedance-matching EOS experiments, multiple-shock EOS, quasi-adiabatic compression of materials, release isentropes, high-strain-rate phenomena, dense-plasma EOS and transport, hydrodynamics and instabilities in strongly coupled plasmas, magnetized target fusion (MTF), and high magnetic field generation. Specific experimental campaigns are now being designed to determine the diagnostic and experimental configuration requirements. As part of a successful Laboratory Directed Research and Development (LDRD) proposal, we will be assisting in the development of a variety of advanced diagnostics to be fielded on Atlas, including linear and nonlinear optical techniques, x-ray diffraction, photoelectron spectroscopy, and flash neutron resonance spectroscopy. All of these techniques are well developed for steady-state measurements, and the development effort lies in adapting them to the dynamic Atlas environment. A number of shots in FY99 have been allocated in the Pegasus imploding liner facility and the Ranchero explosively driven pulsed-power program to develop Atlas diagnostic techniques, explore liner behavior under Atlas conditions, and test certain physical components of the Atlas system.

Fig. 2 Laser driver of the Trident laser facility.

Trident Laser Facility

Trident is the multipurpose laboratory at Los Alamos for conducting experiments requiring high-energy laser-light pulses. As a user facility, it is operated primarily for inertial confinement fusion (ICF) research, high-energy-density physics, and basic research. Features include flexible driver characteristics and illumination geometries, a broad resident diagnostic capability, and flexible scheduling. A dedicated staff maintains and operates the facility and assists visiting experimenters. Target fabrication is available through the Laboratory's Target-Fabrication Facility.

The principal resource at Trident is the laser driver (Fig. 2). It employs a neodymium-doped, yttrium-lithium-fluoride (Nd:YLF) master oscillator and a chain of Nd:phosphate glass-rod and disk amplifiers in a conventional master-oscillator, power amplifier architecture. The oscillator output pulse is temporally shaped, amplified, split into two beams, amplified again, frequency-doubled, transported, and focused onto the target. A third beamline can be used as an optical probe or to provide an x-ray backlighting capability. Its pulse can be either 100 ps in length or the same length and shape as those of the main drive beams. Although the third beamline is normally operated at 527 nm, it can also be operated at 1,054 nm or 351 nm (fundamental and third harmonic output, respectively). The third beam can be timed to become active before or up to 5 ns after the main drive beams. The output of the master oscillator may also be frequency-broadened and "chirped" before amplification to allow compression to subpicosecond pulse lengths.

The main high-vacuum target chamber is a cylinder approximately 150 cm long and 75 cm in diameter. Single- or double-sided illumination of targets is possible through several 20-cm-diameter ports on each end of the chamber. More than 40 smaller ports are available for diagnostic instrumentation. Individual targets are inserted through an airlock. The target insertion and positioning mechanism provides x-y-z and rotation adjustment under computer control with 1-μm linear and 0.01° angular resolution. The three-axis target-viewing system has a 20-μm resolution. The chamber is fitted with a Nova standard six-inch manipulator (SIM) to accept all SIM-based instruments for checkout, characterization, or use. Trident is located in an area of the Laboratory that can accomodate both unclassified and classified research.

Optical diagnostics include illumination and backscattered-light calorimeters, backscattered-light spectrometers, and high-bandwidth (5-GHz) and streak-camera-based power monitors. Target x-ray emission is monitored by filtered, photoconductive diamond detectors and an x-ray streak camera with <10-ps resolution. Gated, filtered x-ray images covering 1 ns in 16 images are provided with 80-ps resolution by a Nova standard gated x-ray imager. Various filtered x-ray power and spectral diagnostics can be installed as needed. These cover the energy range of 0–35 keV. Static x-ray pinhole cameras are also available. Most optical and target diagnostics are available for either the main target chamber or the ultrahigh-irradiance chamber.

Trident is available to Laboratory and outside experimenters. The quality of proposed research and its relevance to Laboratory missions are major criteria in determining what experiments are fielded. Trident is operated by P-24 as a user facility that principally supports Inertial Fusion and other programs in the Nuclear Weapons Directorate. It is funded through and operated for the ICF Program Office. The resources of the Laboratory's Target-Fabrication Facility, operated by the Materials Science and Technology (MST) Division, are also available to assist experimenters in designing, fabricating, and characterizing targets for Trident experiments.

In May 1998, a second target bay and target chamber were added to the Trident Facility as part of the High Energy Density Experimental Laboratory addition to the Trident building. The target chamber was acquired from the University of Rochester Laboratory for Laser Energetics where it was the target chamber used on the original Omega 24-beam laser system. The chamber, focusing lenses, transport optics, frequency conversion crystals, and experimental diagnostics from the original Omega system were all acquired from the University of Rochester in April 1998. A ten-inch manipulator (TIM), which is the new ICF standard for positioning diagnostics, will be installed on this chamber soon, and the facility will be available for check out and testing of TIM-based diagnostics.

Over the next few years, we will upgrade the Trident laser using refurbished Nova laser components. This upgraded laser system is based on a multipass architecture with Nova 31.5-cm disk amplifiers. This new laser system would eventually have eight beamlines operating at 700 J each in 1 ns at 351 nm. Construction of the first phase (two beams) has begun. This new facility will use the Omega 24-beam target chamber, allowing great flexibility in illumination geometries. As envisioned, the Trident upgrade will remain a very flexible, high-shot-rate facility that provides a staging capability to higher energy facilities such as Omega, the future National Ignition Facility (NIF), and Sandia National Laboratory's Z pulsed-power machine. The proposed Trident Upgrade will also greatly enhance present Trident capabilities in performing experiments in laser-matter interactions and other fundamental science topics, and it will serve as an attractor for high-quality scientific research relevant to ICF and stockpile stewardship.

Inertial Confinement Fusion

The ICF program at Los Alamos is a principal component of the national ICF program. The national program is focused on the goal of achieving thermonuclear ignition in the laboratory, one of the grand scientific challenges of the 20th century. This goal is part of the broader mission to provide scientific knowledge, experimental facilities, and technological expertise to support the DOE Stockpile Stewardship Management Plan for nuclear weapons. In pursuit of the ICF mission, P-24 designs, diagnoses, executes, and analyzes the results from experiments at high-energy laser facilities worldwide. P-24 partners with other Los Alamos groups that focus on theory, modeling, and target fabrication to execute the program, with the ultimate goal of understanding laser-matter interaction physics.

Fig. 3 Aerial view of the National Ignition Facility, a state-of-the-art, $1.2B laser facility presently under construction at Lawrence Livermore National Laboratory. This facility will be a key component in the national ICF program, which aims at achieving thermonuclear ignition in a laboratory setting.

NIF, a state-of-the-art, $1.2B laser facility presently under construction at Livermore (Fig. 3), will be the world's most powerful laser by far and the principal focus of the national ICF program. Los Alamos and Sandia have been participating with Livermore in the design and construction of special equipment for this immense laser facility, which will be ~300 ft × 500 ft upon completion and operate at an energy of 1.8 MJ. Design and construction of the facility is currently 35% complete. In the early 1990's Los Alamos scientists collaborated with other members of the National ICF Program to establish the functional requirements and primary criteria that are the basis for this facility. Los Alamos scientists and engineers have been participating since FY93 in the conceptual, preliminary, and detailed designs of a variety of NIF subsystems. Currently, Los Alamos engineers are finishing the detailed design and beginning the engineering (fabrication, installation, and procurement) of four major subsystems: the target chamber service system, the roving mirror diagnostic assembly, the deformable mirror support structure, and the periscope (which includes the mirror support, plasma electrode Pockels cell, and polarizer support structures). P-24 is also a principal participant in the NIF Joint Central Diagnostic Team, and P-24 personnel have worked on the conceptual design for the 351-nm power and energy diagnostics and the preliminary design of a time-resolved x-ray imaging system. In addition, P-24 personnel have been involved with the management of this collaborative project.

NIF is a flexible laser, capable of greatly advancing both the ignition and weapons-physics missions. NIF is designed to drive a capsule filled with deuterium-tritium fuel to thermonuclear ignition by one of two distinct methods: direct or indirect drive. Direct drive involves the implosion of a capsule that is directly illuminated by the laser beams. Indirect drive involves laser illumination of the interior walls of a cavity (called a hohlraum) that contains the capsule. The hohlraum converts the laser energy into x-rays, which illuminate and implode the capsule very symmetrically, analogous to the process of baking an object evenly in an oven. Since both methods have different potential failure modes, both are being pursued to increase the likelihood of achieving ignition on NIF.

Considerable challenges face us in preparation for achieving fusion ignition on NIF, which will first be attempted using indirect drive. These challenges include developing novel diagnostic methods and instruments, and improving our understanding in several scientific areas, including laser-plasma instabilities, hydrodynamic instabilities, hohlraum dynamics, and dynamic properties of materials. P-24 has contributed significantly in all of these areas with target-physics experiments using present lasers: Nova at Livermore, Omega Upgrade at the University of Rochester, and Trident at Los Alamos.

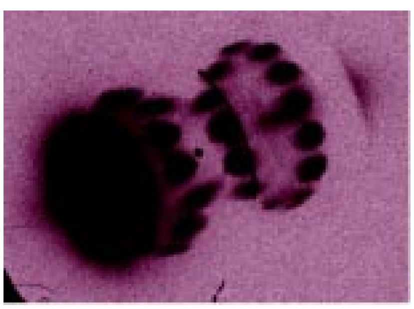
P-24 personnel have devoted considerable effort to studying laser-plasma parametric instability (LPI) processes. We have focused on Raman and Brillouin scattering, and on the novel phenomena of beam deflection by plasma flow. LPIs pose a significant threat to ignition hohlraums because they could potentially scatter most of the laser light, decreasing both the drive efficiency and the capsule illumination symmetry. During the past two years, P-24 has pursued a dual-track strategy of complementary experimental campaigns at Nova and Trident. P-24 researchers have applied the extensive Nova diagnostic suite on ignition-relevant hohlraums designed at Los Alamos, the most NIF-like plasmas ever made.

These LPI experiments on Nova are now complete, and data analysis is proceeding to complete our extensive LPI database, which will guide theoretical modeling and future experiments. The database includes calorimetry and time-resolved spectrometry of the scattered light, time-gated images of the scattered light within the target plasma, and other measurements that confirm the target plasma conditions in the hohlraum design. The scattered light measurements were done as important plasma parameters (*e.g.*, plasma density, ion species, and laser parameters like intensity, f number, and beam smoothing) were changed one at a time. So far, this approach has allowed us to identify qualitatively important trends in LPI processes of NIF-like plasmas, constrain emerging theoretical LPI models, and assess the threat of LPIs to ignition prior to NIF construction.

Our LPI experimental thrust has shifted to the application of new state-of-the-art capabilities and diagnostics on Trident long-scale NIF-relevant plasmas to allow more detailed measurements and comparisons of theory with experiment. These new capabilities include a nearly diffraction-limited interaction beam capable of the intensity range relevant to parametric instabilities in ignition-hohlraum plasmas. Imaging Thomson scattering now yields direct measurements of the spatial profile of important plasma parameters, such as electron density and temperature, ion temperature, plasma-flow velocity, and the location of the electrostatic waves responsible for laser scattering. We now can thoroughly benchmark the radiation-hydrodynamic codes used to design the plasma conditions in the first place. The coupling of these recent diagnostics with reflected and transmitted beam diagnostics, such as those previously implemented at Nova, already has allowed unprecedented studies of the time evolution of parametric instabilities and beam deflection. In the longer term, the plan is to exploit the fact that the single-hot-spot Trident system is sufficiently small for direct modeling by an emerging suite of codes incorporating new theoretical models. From these comparisons, we hope to develop simplified “reduced-description” models that are suitable for NIF-scale plasmas.

P-24 personnel have had important successes in advancing our understanding and capabilities in hohlraum dynamics. We have extended our understanding of and capabilities with cylindrical hohlraums, which will be used in the first indirect-drive ignition attempts on NIF. On Nova, we demonstrated control of beam deflection and its effects on capsule-illumination symmetry by spatial smoothing of the laser-beam. On Omega Upgrade, we collaborated with Livermore researchers in an important experimental series that exploited the larger number of Omega beams. As many as 40 beams were arranged into multiple beam cones (Fig. 4). These experiments constituted a first step in the development of “beam phasing,” in which beams were arranged into multiple beam cones, forming multiple rings of beam spots on the inner surface of a cylindrical hohlraum. Beam phasing will be necessary on NIF to tune both the time-integrated and time-dependent capsule-flux asymmetry by adjustment of the beam pointing and the power history in the different rings. These initial experiments have demonstrated our ability to model hohlraums incorporating multiple beams cones. We have also demonstrated unprecedented time-integrated illumination symmetry using an advanced hohlraum design developed at Los Alamos for deployment at Omega Upgrade, featuring a spherical radiation case and laser-

(a)



(b)

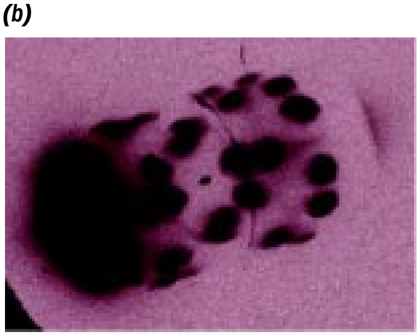


Fig. 4 Cylindrical hohlraums with single-ring (a) and two-ring (b) configurations of beam spots. Experiments with such hohlraums are the first step in developing “beam phasing,” in which many beams are arranged into multiple beam cones to control implosion symmetry.

entrance holes in a tetrahedral arrangement (see Fig. 5). Since the unique mission of Omega Upgrade is direct drive, the beams enter the target chamber in a spherical geometry, a non-optimal arrangement for cylindrical hohlraums. But tetrahedral hohlraums in Omega Upgrade can use all 60 beams and drive higher energy implosions than cylindrical implosions, an added advantage to the improved symmetry.

There was significant activity and progress in the area of hydrodynamic instability. In the NIF, capsules with cryogenic fuel will have to be compressed to large convergence ratios (about 30) in order to ignite. Convergence is ultimately limited by hydrodynamic instability. To date, laser-driven capsule implosions have only achieved moderate convergence ratios (below 10), due at least in part to the known limitations of past laser systems, including Nova. During the past two years, P-24 fielded the initial attempts at implosions of double-shell capsules, first at Nova and subsequently at Omega Upgrade, in tetrahedral hohlraums.

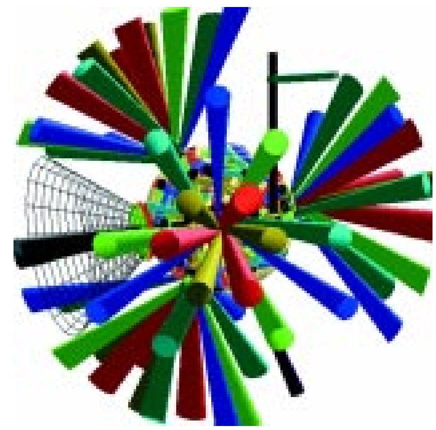


***Fig. 5** 3-D schematic of a spherical radiation case with tetrahedral symmetry. This design allows for use of all 60 Omega Upgrade laser beams to drive a higher-energy implosion with improved symmetry.*

Double shell capsules are an attractive alternative for NIF because they do not require cryogenics for ignition, although they are potentially more hydrodynamically unstable than single-shell capsules. The improved illumination symmetry in tetrahedral hohlraums now allows reasonable attempts at high-convergence implosions with double-shell capsules prior to deployment of the Omega Upgrade cryogenics system.

The first experimental series with Omega Upgrade capsules did not reach the predicted performance. Potential culprits have been identified and further investigation is proceeding. P-24 hydrodynamics research has also focused on cylindrical implosion targets, which are much easier to diagnose than capsules and yet retain important convergent effects (see the research highlight on this topic in Chapter 2). P-24 researchers have completed a study of the nonlinear growth of multi-mode perturbations in x-ray-driven cylindrical targets due to the ablative Raleigh-Taylor (RT) instability on Nova, and the results were in good agreement with theoretical modeling. Moreover, there was spectacular success in deploying direct-drive cylindrical implosions of Los Alamos design, capable of significantly higher RT growth than the indirect-drive design. Our initial single-mode RT experiment showed significantly lower growth factors than predicted, and additional investigation is proceeding.

In collaboration with other groups in the Laboratory's Physics, Applied Theoretical and Computational Physics (X), and Dynamic Experimentation (DX) Divisions, as well as Oxford University, the University of California at San Diego, Sandia, and Livermore, P-24 is using the Trident laser system to pursue studies of the dynamic properties of materials that are of interest to the ICF Program and to weapons science. The Trident laser is used to drive high-pressure (from tens of kilobars to several megabars), temporally shaped shocks into condensed materials under study. Separate beams of the laser system can be used to create accurately synchronized, powerful x-ray and optical pulses that are used for probing the shocked material. Using this configuration, the group has developed new diagnostic methods such as transient x-ray diffraction (TXD). TXD has in turn been used to measure the dynamic properties of phase changes in materials.

The methods developed on Trident are being applied to materials of central interest to ICF, such as beryllium. One of the ultimate goals of this research program is detailed characterization of beryllium alloys such as beryllium-copper. These materials will be used as the ablator in advanced, Los Alamos-designed ignition capsules with superior hydrodynamic stability. Exact determination of the melt transition in these materials is crucial for predicting their hydrodynamic behavior during implosion. The temporally resolved measurements of solid-solid phase transitions that have already been demonstrated are an important precursor to measurement of melt dynamics.

P-24 personnel deployed several diagnostics and support systems for the ICF program. The biggest effort was associated with Omega Upgrade. An optical Cassegrain microscope, which fits in the standard ten-inch reentrant diagnostic manipulator, was fielded successfully and is already in use for Los Alamos campaigns. This instrument has added the capability to diagnose the propagation of shocks (and thus hohlraum radiation temperature) by detecting the shock breakout from a calibrated material sample. P-24 has also deployed the Omega “bang-time” diagnostic, part of the customary diagnostic suite for capsule implosions. The Kirkpatrick-Baez x-ray microscope previously deployed by P-24 at Omega was the beneficiary of a major upgrade. A target metrology station for Omega, engineered and deployed by P-24, has proven to be another success.

Closer to home, a local x-ray calibration facility has been set up to test various x-ray diagnostics under development in P-24 and to maintain existing ones. This facility should eliminate the wasteful use of laser system shots for such purposes. Looking towards our future on NIF, P-24 completed the conceptual design for the time-resolved x-ray imaging system, a Phase-1 NIF diagnostic. Moreover, we have demonstrated successfully the rapid-pad-polishing technique for NIF optical fabrication, which is now moving to the production stage.

High Energy Density Experiments in Support of Stockpile Stewardship

P-24 performs laser and pulsed-power-based experiments that are intended to enhance understanding of the basic physical processes that underlie nuclear weapons operation. In collaboration with weapons designers and other theoreticians, these experiments are designed to address issues in areas such as radiation hydrodynamics, fluid instabilities, shock wave physics, and materials science. The experiments use the Trident laser and the Pegasus pulsed-power machine at Los Alamos, and also larger facilities including the Nova laser, the Omega laser, the Helen laser at the Atomic Weapons Establishment (AWE) Laboratory in the United Kingdom, and Sandia's Z pulsed-power machine. We have formed strong world-wide collaborations in the disciplines central to high energy density physics.

Current work in the group includes

- nonlinear fluid instability studies driven by a variety of pressure sources;
- imploding liner studies of the basic nature of material friction;
- propagation of structured shocks in a variety of media (Fig. 6);
- development of transient x-ray diffraction for the study of solid phase changes, plastic flow, and other materials phenomena;
- study of the implosion of cylindrical and spherical shells with various defects;
- study of high-energy, laser-based x-ray radiography for diagnosis of fluid instability experiments; and
- study (in collaboration with Sandia) of the fundamental properties of beryllium that are of interest to inertial fusion and other applications.

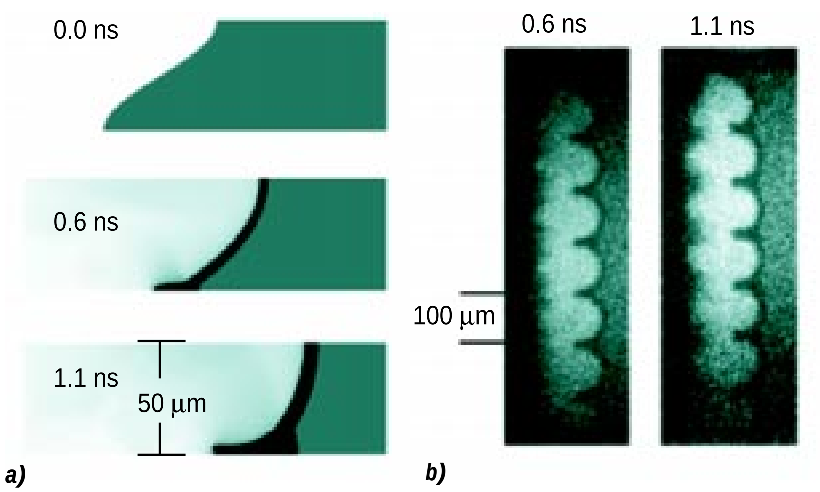


***Fig. 6** A simulation of a half-wavelength segment (a) and experimental data for five to six full wavelengths (b) of a temporally shaped shock propagating in brominated polystyrene. This exeriment was designed and fielded at the Nova laser by Los Alamos personnel.*

In the pursuit of our research, we are developing advanced diagnostic measurement systems. This work includes research on very high-resolution x-ray imaging that will be applied to hydrodynamic, shock-wave, and materials experiments. We also pursue research in fundamentally improving the quantitative analysis of temporally gated x-ray imaging.

Magnetic Confinement Fusion

Magnetic fusion energy research, and its associated science, is an important constituent of P-24's plasma physics portfolio. We are capitalizing on the recent strategic shift in national fusion research priorities, to increase the emphasis on innovative fusion confinement approaches. To that end, P-24 is working with the Los Alamos Magnetic Fusion Energy (MFE) Program office to develop new low-cost concepts for fusion energy. Central to this effort is magnetized target fusion (MTF), a truly different fusion concept intermediate in density between traditional magnetic fusion and inertial fusion. We specifically propose to form and preheat a compact toroid target plasma using well-established techniques, and then compress this target plasma with imploding liner technology developed by DOE defense programs (Fig. 7).

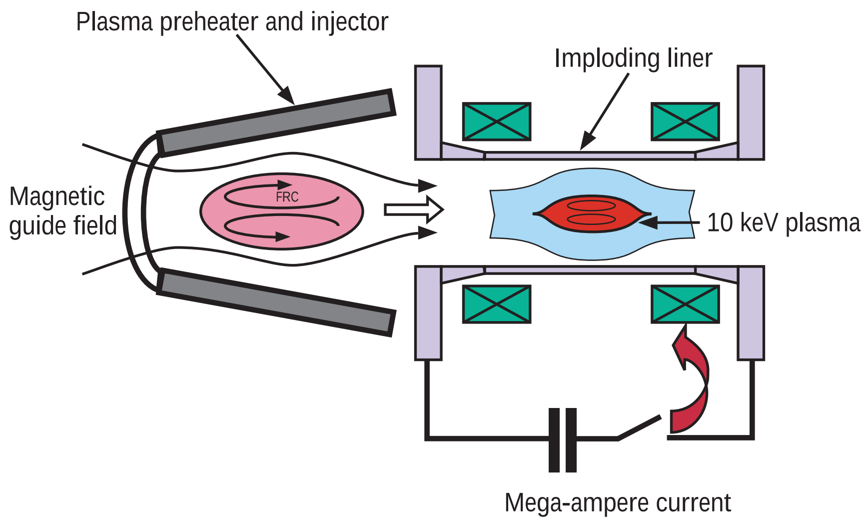


Fig. 7 A schematic of the Los Alamos MTF experiment. A dense, field-reversed configuration (FRC) target plasma is formed and translated into a 10-cm-diameter, 30-cm-long aluminum liner (flux conserver). The liner is subsequently imploded to a final diameter of 1 cm at velocities up to 1 cm/μs. The compressed plasma will reach 5 to 10 keV under adiabatic compression if losses can be kept low.

Three technical considerations explain why research in the MTF density regime is important. First, fusion reactivity, which scales as density squared, can be increased by many orders of magnitude over conventional MFE. Second, all characteristic plasma scale-lengths decrease with density. Hence, system size is naturally reduced at a high density. Third, magnetic insulation greatly reduces the required power and precision to compressionally-heat a plasma to fusion-relevant conditions compared with ICF, and brings the pulsed-power requirements for adiabatic plasma heating within reach of existing facilities. The future path for engineering development of MTF as an economic power source is less well-defined than for the more mature approaches of MFE and ICF. However, a number of possibilities are being discussed, and our research program will include scoping studies to identify the most promising approaches. If successful, MTF will achieve high performance fusion conditions with soon-to-be-realized pulsed-power facilities such as Atlas.

Historically, Los Alamos has had significant involvement in developing alternate approaches to fusion. This precedent has guided our development of collaborative programs with Columbia University, the University of Washington, Livermore, and the Princeton Plasma Physics Laboratory. In all four collaborations, we employ our engineering, physics, and diagnostics expertise to aid the development of exciting fusion concepts.

Our collaboration with Columbia University produced high-power amplifiers to suppress magnetohydrodynamic activity in the high-beta (HBT-EP) tokamak experiment. In collaboration with the University of Washington, we are developing a high-power modulator to drive plasma current in a field-reversed configuration (FRC) experiment by means of rotating magnetic fields. FRCs belong to the compact toroid class of fusion approaches and promise efficient magnetoplasma confinement with simple, compact reactor configurations. Our University of Washington collaboration current-drive experiments are central to the notion of steady-state FRC operation.

Two new experimental collaborations are also underway. We are joining with Livermore to take the next step in sustained spheromak confinement research. The Sustained Spheromak Physics Experiment, under construction at Livermore, was designed to achieve high plasma performance under quasi-steady-state conditions. Los Alamos expertise, developed over years of research on the Compact Torus Experiment spheromak, will be an important contributor to the success of this effort. We are also joining the national research team on the National Spherical Torus Experiment under construction at the Princeton Plasma Physics Laboratory. This experiment will investigate the confinement properties of very low-aspect-ratio tokamaks with a view to achieving efficient (high-beta) confinement in a compact toroidal system.

Applied Plasma Technologies

P-24 develops and uses advanced plasma science and technology to solve problems in defense, the environment, and industrial manufacturing. The group has achieved international status and recognition in this pursuit, including two recent R&D 100 awards. The first R&D 100 award, presented in 1996, was in recognition of the development of the PLASMAX system, which takes advantage of plasma sheath properties combined with mechanical vibration to rapidly and effectively clean semiconductor wafers without water or other liquid solvents. The second R&D 100 award, presented in 1997, recognized the efforts of a multidisciplinary group (both Laboratory and industrial personnel) in the initial commercialization of plasma source ion implantation (PSII) (see the discussion below and the research highlight on this topic in Chapter 2). Major technology-development and program elements within the group include the following:

Atmospheric-Pressure Plasma Jet

A nonthermal, uniform-glow discharge at atmospheric pressure in a cylindrical cavity with high gas-flow rates produces reactive radicals and metastables persisting for fractions of a second at atmospheric pressure. These reactive species remove surface contaminants and films, providing a new means of cleaning objects and substrates (Fig. 8). Current programs include chemical and biological decontamination for the neutralization of chemical agents on surfaces and graffiti removal.

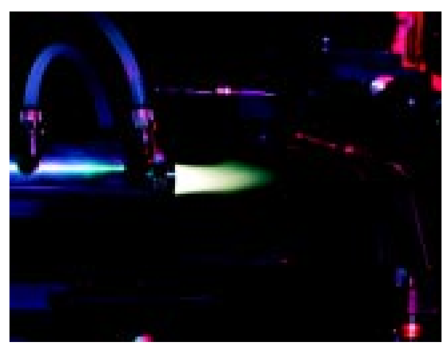


***Fig. 8** The atmospheric pressure plasma jet in operation, with a reactive gas stream exiting from the source.*

Intense, Pulsed Ion Beams and Accelerated Plasmas

Several promising applications of intense ion beams and pulsed accelerated plasmas have emerged in the past few years. These include processing of materials, including surface modification through rapid melt and resolidification, ablative deposition for producing high-quality coatings, and nanophase powder synthesis; production of intense neutral beams for the next generation of tokamaks; and intense, pulsed neutron sources for the detection of nonmetallic mines, neutron radiography, neutron resonance spectroscopy, and spent nuclear fuel assay. We are nearing completion of two devices that address these applications: an intense, repetition-rated ion accelerator known as the continuous, high-average-power microsecond pulser (CHAMP), and an accelerated plasma source known as the magnetoplasma processing tool (MPT).

CHAMP will produce a 12-kA, 250-keV, 1-μs ion beam from any gas puffed into its magnetized anode. This beam is ballistically focused to a 25- to 100-cm^2 spot, resulting in energy fluxes of tens of J/cm^2—enough to ablate the surface material. Lower energy fluxes can be obtained by working out of the focal plane. Due to the low gas-loading of this anode and the design of the accelerator, this technology is capable of being operated at 30 Hz, although as constructed CHAMP will operate at about 1 Hz. Calculations suggest that by hitting a tritiated metal target with a deuteron beam, a microsecond pulse of 2×10^{12} DT neutrons could be produced in a device sufficiently portable to be fielded at experimental sites throughout the Laboratory.

The MPT produces a 10- to 30-kV accelerated plasma of any gas, and is capable of delivering up to 4 J/cm^2 over 1,000 cm^2 in a 200 μs pulse at an electrical-to-directed energy efficiency of up to 50%. Like CHAMP, this device can be transported easily. Applications include rapid, wide-area treatment of materials, such as etching and crosslinking of polymer surfaces.

Plasma-Source Ion Implantation and Cathodic Arcs

PSII is a non-line-of-sight method for implanting ions from a plasma into a target (usually, but not necessarily a conducting material) to achieve beneficial surface modifications. Typically, ions in plasma produced from a gaseous precursor are used, but cathodic arc technology allows metal ions to be implanted as well. PSII may be seamlessly combined with plasma-based surface-coating technologies to form highly adherent, relatively thick (many microns) coatings of materials such as diamond-like carbon (DLC) and ceramic metal oxides. Past and present programs include development of plasma-implanted and plasma-deposited erbia coatings in support of the weapons surety program; molten-plutonium-resistant coatings for near-net-shape casting molds;

highly adherent refractory coatings for wear- and corrosion-resistant gun barrels for the Army; and plasma-based surface treatment and adherent coatings for industrial tooling. The industrial support for research and development (R&D) in this area is part of a National Institute of Science and Technology (NIST) Advanced Technology Program with more than a dozen industrial partners.

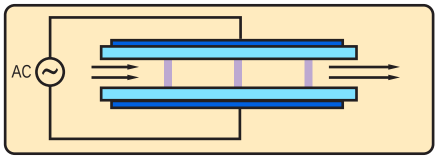
Silent-Electrical and Pulsed-Corona Discharges

Nonthermal plasmas (NTPs), sometimes called nonequilibrium or "cold" plasmas, are characterized by conditions in which the various plasma species are not in thermal equilibrium—that is, electrons, ions, and neutral species have different temperatures, with the less massive electrons having the highest temperature (*e.g.*, 1–10 eV). Such plasmas are good sources of highly reactive oxidative and reductive species and plasma electrons. Via these reactive species, one can direct electrical energy into favorable gas chemistry through energetic electrons. NTPs can be easily created by an electrical discharge in a gas. Two example NTP reactors, a silent-discharge plasma reactor and a pulsed-corona reactor, are shown in Fig. 9. Both use the mechanism of transient electrical discharge streams to produce energetic electrons and associated active species in the process gas.

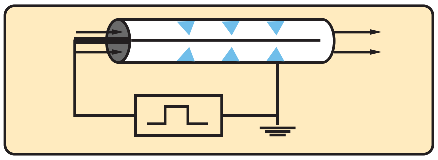
We are applying atmospheric-pressure NTP processing to hazardous-chemical destruction, pollution control, and chemical synthesis. The hazardous-chemical-processing and pollution-control applications range from the treatment of hydrocarbon and halocarbon compounds (many solvents) that are entrained in soil and water or are emitted as stack gases, to the treatment of oxides of nitrogen (nitric oxide, in particular) in flue and engine-exhaust gases. Our work has spanned the regimes of bench-scale studies to actual field demonstrations of this technology. Our more recent interests are directed toward the synthesis of higher-order hydrocarbon fuels from methane. Research in the area of NTPs represents a fusion of the fields of electrical-discharge physics, plasma chemistry, and pulsed power.

Further Information

For further information on all of P-24's projects, refer to the project descriptions in Chapter 3. Some of our major achievements are also covered as research highlights in Chapter 2. These include our work at the Trident facility, our current PSII developments, cylindrical and spherical implosion research at Nova and Omega, and development of an infrared imaging bolometer for use in fusion plasma research.



Silent discharge plasma reactor
(dielectric-barrier discharge)



Pulsed corona reactor

***Fig. 9** Schematic drawings of silent-discharge plasma and pulsed-corona reactors. These reactors use an electrical discharge in a gas to create nonthermal plasmas that can be used for such purposes as destroying hazardous chemicals, controlling pollutants, and synthesizing chemicals.*

P-25: Subatomic Physics

Andrea P. T. Palounek,
Group Leader

Michael J. Leitch,
Deputy Group Leader

Introduction

The Subatomic Physics Group (P-25) is engaged primarily in fundamental nuclear and particle physics research. Our objective is to conduct diverse experiments that probe various aspects of subatomic reactions, providing a more thorough understanding of the basic building blocks that make up our universe. Although our main focus is basic research, there is also a strong and growing effort to turn the group's skills and capabilities to applied programs such as proton radiography. To conduct our research, we often participate in large-scale collaborations involving physicists from universities and institutions around the world, and we participate in and lead experiments at a variety of facilities. Currently, we are conducting research and developing new programs at Los Alamos National Laboratory and other laboratories, including Brookhaven National Laboratory and Fermi National Accelerator Laboratory (Fermilab). The following sections highlight the significant experiments and activities that we are currently pursuing.

Hypernuclei Physics

One of our key interests over the past several years has been the study of lambda (λ)-hypernuclei, where the λ replaces a neutron within nuclei, to explore the strong interaction (the force that holds the nucleus of an atom together). In 1994, we proposed experiment 907 (E907) at Brookhaven's Alternating-Gradient Synchrotron (AGS) to study the feasibility of using the (K^-,π^0) reaction (in which a negative kaon decays to a neutral pion) as a novel tool to produce λ-hypernuclei with energy resolutions significantly better than those produced in the previous (K^-,π^-) and (π^+,K^+) experiments (in which negative kaons decay to negative pions and positive pions decay to positive kaons, respectively). E907 should also be capable of measuring the π^0 weak-decay modes of λ-hypernuclei, which have never been studied before. The LANSCE Neutral Meson Spectrometer (NMS) and associated equipment were moved to the AGS for this experiment. A new data acquisition system and a new array of active target chambers were also successfully installed. Preliminary measurements have provided the first hypernuclear spectrum using the (K^-,π^0) reaction. In addition, the π^0 energy spectrum resulting from the weak-decay of light λ-hypernuclei has also been measured. Data collection has been completed and the data are currently being analyzed.

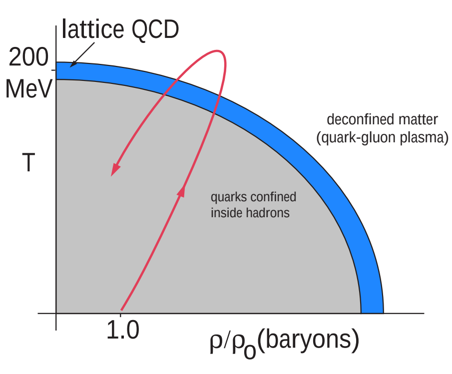


***Fig. 1** Lattice QCD calculations predict that at higher temperatures and densities, there will be a transition of matter from the confined state to the deconfined state, as shown by the solid band. Research with RHIC will explore this transition of matter.*

The PHENIX Program at RHIC

P-25 has also been exploring the subatomic physics that defined the universe at its beginning. Big Bang cosmology pictures a time very early in the evolution of the universe when the density of quarks and gluons was so large that they existed as a plasma, not confined in the hadrons we know today (neutrons, protons, pions, and related particles) (Fig. 1). In 1999, when operations commence at Brookhaven's Relativistic Heavy-Ion Collider (RHIC), it should become possible to create a small sample of such primordial quark-gluon plasma in the laboratory and study its exotic properties. The challenge facing the international collaborators involved in the RHIC program is to find the signatures of the fleeting transition into this deconfined phase of matter. Extending the Physics Division's long history of experiments at the energy frontier, P-25 is playing a major role in defining the physics program for RHIC.

P-25 is also playing a key role in constructing two major subsystems for the PHENIX detector, one of two major collider detectors at the RHIC facility. The PHENIX collaboration currently consists of over 400 physicists and engineers from universities and laboratories in the U.S. and nine foreign countries. Our work focuses on the multiplicity/vertex detector (MVD) and the muon subsystem. The MVD is the smallest and among the most technically advanced of the PHENIX systems. It will be located very close to the region where the two beams of 100-GeV nucleon ions intersect. Its function is to give the precise location of the interaction vertex and to determine the global distribution and intensity of secondary charged-particle production, which is a crucial parameter in fixing the energy density achieved in the collision fireball.

The muon subsystem, the largest of PHENIX's subsystems, consists of two large conical magnets and associated position-sensitive tracking chambers at opposite ends of the detector. Muons are identified by recording their penetration of a series of large steel plates interspersed with detection planes, all of which follow the magnets at each end of the detector. The muon subsystem plays a central role in P-25's physics agenda at RHIC. It is optimized for examining experimental observables at very high temperatures and densities, at which the strong force is smaller and easier to calculate using perturbative quantum chromodynamics (QCD).

RHIC is currently scheduled to begin operations in late 1999, and first results are expected in 2000.

High-Energy Nuclear Physics

Another area of study in P-25 is parton distribution in nucleons and nuclei, and the nuclear modification of QCD processes such as production of J/ψ particles (made up of a pair of charm/anti-charm quarks). We are currently leading a research program centered on this topic at Fermilab. This program (which is discussed further in a research highlight in Chapter 2) began in 1987 with measurements of the Drell-Yan process in fixed-target proton-nucleus collisions (see Fig. 2). These measurements showed that the antiquark sea of the nucleon is largely unchanged in a heavy nucleus. In our most recent measurements during the NuSea Experiment (E866), we also showed that there is a large asymmetry between down and up antiquarks, presumably due to the nucleon's pion cloud (Fig. 3). In addition we showed that the production of heavy vector mesons such as the J/ψ is strongly suppressed in heavy nuclei. We mapped out this effect over a broad range of J/ψ energies and angles. Although the causes of this suppression are not yet fully understood, it is already clear that absorption in the final state

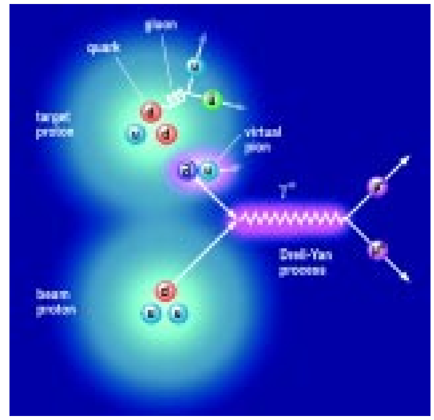


Fig. 2 A proton consists of three valence quarks held together by gluons in a sea of quark-antiquark pairs. These pairs may be produced by gluon splitting, a symmetric process generating nearly equal numbers of anti-down, $\bar{d}$, and anti-up, $\bar{u}$, quarks, or from virtual-pion production, an asymmetric process that generates an excess of $\bar{d}$. We can determine $\bar{d}/\bar{u}$ by measuring the properties of the muon pairs produced in the Drell-Yan process, which occurs when a quark in a proton beam strikes a sea antiquark in a target.

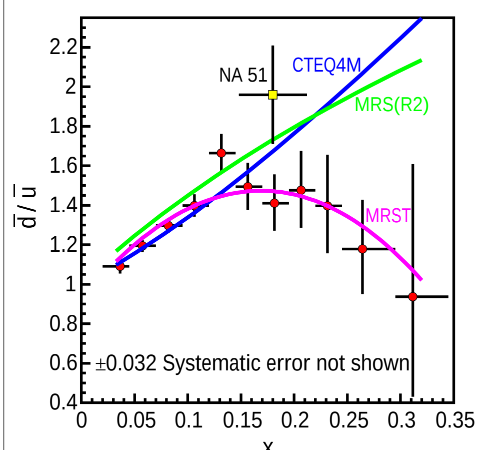


Fig. 3 The ratio of $\bar{d}$ to $\bar{u}$ in the proton from the FNAL E866 NuSea data as a function of the fraction of the proton's momenta carried by the quark, x. NA51 was the only previous measurement of this quantity. The curves represent various parameterizations of $\bar{d}/\bar{u}$. The curve that best matches that data, labeled "MRST," was proposed only after the FNAL E866 NuSea data were published.

plays an important role, as do energy-loss of the partons and shadowing of the gluon distributions. Data analysis is nearly complete, and continuing experiments at Fermilab have been proposed.

Liquid Scintillator Neutrino Detector

P-25 also conducts experiments to explore the possibility of neutrino oscillation, which has great implications in our understanding of the composition of the universe. The Liquid Scintillator Neutrino Detector (LSND) experiment at LANSCE has provided evidence for neutrino oscillations, revealing an excess of oscillation events in both the muon-antineutrino to electron-antineutrino ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$) and muon-neutrino to electron-neutrino ($\nu_\mu \rightarrow \nu_e$) appearance channels. These two channels are independent of each other and together provide strong evidence for neutrino oscillations in the $\Delta\left(m^2\right) > 0.2\ \mathrm{eV}^2$ region. The LSND results, therefore, imply that at least one of the neutrino types in each of these appearance channels has a mass greater than 0.4 eV, a contradiction to standard models that assume neutrinos have no mass. Based on estimates of the number of neutrinos present in the universe, the LSND results suggest that neutrinos contribute more than 1% to the mass density of the universe. The existence of neutrino oscillations has great significance for nuclear and particle physics as well because it means that lepton number is not conserved and that there is mixing among the lepton families, which contradicts the standard models. The LSND experiment, which had its last run in 1998, has also made precision measurements of neutrino-carbon and neutrino-electron scattering, which is of interest for testing the weak interaction.

Booster Neutrino Experiment

As an extension of the work conducted during the LSND experiment, P-25 has been pursuing the Booster Neutrino Experiment (BooNE), which will make a definitive test of the LSND neutrino oscillation results. This experiment will also be conducted at Fermilab. The BooNE detector will consist of a 12-m-diameter sphere filled with 770 tons of mineral oil and covered on the inside by 1,220 phototubes recycled from the LSND experiment (Fig. 4). The detector will be located 500 m away from the neutrino source, which will be fed by Fermilab's 8-GeV proton booster. The proton booster will run nearly continuously, and if the LSND results are indeed due to neutrino oscillations, BooNE will observe approximately 1,000 $\nu_\mu \rightarrow \nu_e$ oscillation events after one year of operation. Furthermore, if oscillations are observed, BooNE will be able to make precision measurements of the oscillation parameters and test for charge-conjugation parity violation in the lepton sector. The BooNE detector should be operational by the end of 2001, and first results are expected a year later.

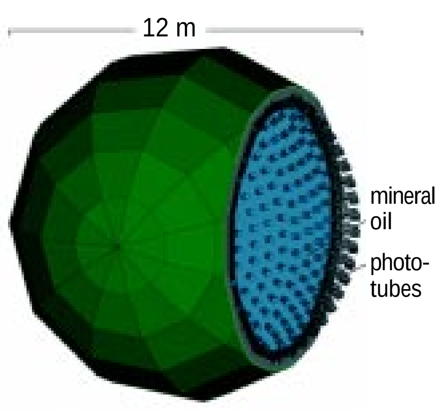


Fig. 4 Conceptual view of the BooNE detector, which will provide a definitive test of the LSND evidence for neutrino oscillations.

MEGA

The apparent conservation of muon number remains a central problem of weak interaction physics, and is thus another area of research in P-25. Experimental evidence to date shows that muons consistently decay into an electron and two neutrons. However, the particle physics community is continually searching for instances that violate muon number conservation, which would give insight into possible extensions of the minimal standard model of weak interactions. MEGA was an experimental program designed to make such a search at the Los Alamos Meson Physics Facility (LAMPF), now known as LANSCE. MEGA, which searched for muon decays yielding an electron and a gamma ray (hence, the acronym), completed its data collection in 1995. The extraction of kinematic properties for all of the muon decay events that potentially meet the MEGA criteria is now complete, and the final sample of about 5,000 events is under careful scrutiny. The combined data from the summers of 1993–1995 are expected to yield a statistical precision that improves the current world sensitivity to this process by a factor of 25 to roughly 3×10^{-12}.

Rho

As part of the MEGA program, the MEGA positron spectrometer was used to measure the Michel parameter ρ (rho), which governs the shape of the polarization-independent part of the energy spectrum for positrons emitted in normal muon decay. The standard model predicts ρ to be 0.75; based on experimental results to date, it is known to be within 0.3% agreement with that value. Deviations from 0.75 might indicate the need for right-handed currents in the standard model. In our experiment, the energy spectrum for over 2×10^8 positrons was recorded and data were taken under several conditions to help with the analysis of systematic errors. Despite these precautions, we anticipate that energy-dependent systematic errors will limit the accuracy of the result to a level that is currently being evaluated. Analysis of the data is scheduled for completion in 1999.

Electric Dipole Moment of the Neutron

P-25 is also participating with the Neutron Science and Technology Group (P-23) in a Laboratory project aimed at improving the limit on the electric dipole moment (EDM) of the neutron. Our interest in this topic is driven by the recent observation of violation of time reversal invariance in the neutral kaon (K^0) system. Many theories have been developed to explain this time-reversal-invariance violation, but most have been ruled out because they predict a sizable EDM for the neutron, which experiments have yet to verify. Today, new classes of highly popular models, such as supersymmetry, predict EDM values that are potentially within the reach of experiment. In addition, if the observed baryon-antibaryon constitution of the universe is due to time-reversal-violating symmetry breaking at the electroweak scale, the range of predicted EDM values is also measurable. We are currently working towards experimentally verifying the feasibility of conducting an experiment that should improve the limit on the neutron EDM by two orders of magnitude to 4×10^{-28} e*cm.

Fundamental Symmetry Measurements with Trapped Atoms

With the advent of optical and magnetic traps for neutral atoms, a new generation of fundamental symmetry experiments has arisen that exploit point-like, massless samples of essentially fully polarized nuclei. In P-25, we are pursuing a measurement of the beta-spin correlation function in the beta decay of ^{82}Rb confined to a time orbiting potential (TOP) magnetic trap as a means to probe the origin of parity violation in the weak interaction (see the research highlight on this topic in Chapter 2). We also envision a new generation of atomic-parity nonconservation experiments that test the neutral current part of the weak interaction. In the latter experiments, measurements of the beta-spin correlation function with a series of radioactive isotopes of cesium and/or francium could eliminate atomic structure uncertainties that presently limit the ultimate precision of beta-spin correlation function measurements. This should improve the quality of our results.

Ultracold Neutrons

P-25 is also participating with P-23 in experiments to provide better sources of UCN, which can be trapped to study neutron properties. Solid deuterium converters have been proposed as a source of UCN for some time. Recently, experiments conducted in the Physics Division have made it clear that coupling a solid deuterium moderator to the high cold-neutron densities available from a pulsed spallation neutron source, such as the Los Alamos Proton Storage Ring, may provide a UCN source with several orders of magnitude higher neutron density than reactor driven sources such as the Institute Laue-Langevin source.

Theory

In addition to the fundamental research conducted in our group, P-25 has a strong theory component, which consists of a staff member and a number of short- and medium-term visitors from universities and laboratories throughout the world. Theoretical research focuses on basic issues of strong, electromagnetic, and weak interactions topics that complement the present activity of the experimental program and that impact possible future scientific directions in the group. As such, our theoretical component facilitates interaction between experimental and theoretical activities in the nuclear and particle physics community and contributes to a balanced scientific atmosphere within the group. Recent theoretical activity has focused on neutrino interactions and masses, parity violation in chaotic nuclei, deep inelastic scattering, hadron properties in free-space and in nuclei, and QCD at finite temperatures.

Proton Radiography

Although our main focus is basic research, P-25 also has several applied programs, such as proton radiography. There are two goals for the proton radiography program. The first is to demonstrate that high-energy proton radiography is a suitable technology for meeting the goals established for the advanced radiography program; the second is to develop the capability of 800-MeV proton radiography for meeting immediate programmatic needs. These goals are highly coupled since many of the techniques developed for 800-MeV radiography can be used at higher energies. Most of our effort in the last year was focused on the 800-MeV program because funding restrictions limited progress in our planned 25-GeV demonstration at Brookhaven's AGS. We are currently exploring the possibility of building a 50-GeV machine, the proton radiography interim-step machine (PRISM) that will be dedicated to proton radiography experiments (Fig. 5). For more information on our proton radiography efforts, refer to the research highlight on this topic in Chapter 2.

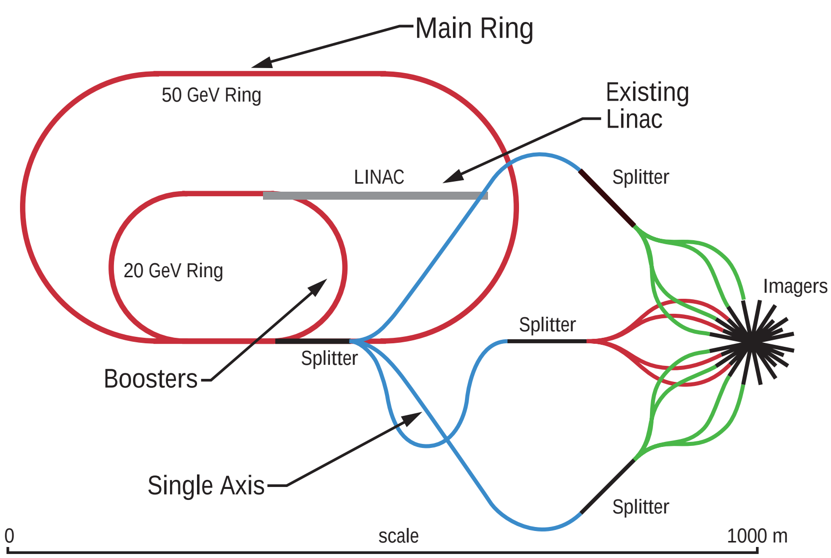


***Fig. 5** Concept of the proton radiography Advanced Hydrotest Facility (AHF). PRISM, a subset of the AHF, would include the linac injector, the main 50-GeV acceleration ring, a single-axis extracted beam line, a firing point, and a lens system.*

Quantum Computation using Cold, Trapped Ions

In another applied program, P-25 is collaborating with P-23 to develop quantum computation technology. Quantum computation is a new computational paradigm that is much more powerful than classical computation because it allows computing with quantum-mechanical superpositions of many numbers at once. In a quantum computer, binary numbers will be represented by quantum-mechanical states ("qubits"). We are developing a quantum-computational device in which the qubits will be two electronic states of calcium ions that have been cooled with a laser to rest in an ion trap. Once these ions are resting in the trap, we will perform quantum logical operations with a laser beam that is resonant with the qubit transition frequency and is directed at individual ions. We have recently succeeded in trapping and imaging a cloud of calcium ions using two titanium-sapphire lasers, one frequency-doubled to 397 nm, the other to 866 nm. Future experiments will focus on increasing the number of ions that are simultaneously trapped, which will move us closer to realizing a functioning quantum computation system.

Carbon Management and Mineral Sequestration of CO_2

P-25 is also focussing on ways to solve global environmental issues, such as the overabundance of carbon dioxide (CO_2) in the atmosphere. Today, fossil fuels account for 80–85% of total world energy use. The reasons for this include their abundant supply, high energy-density, public acceptance, ease of use and storage, existing infrastructure, and, most importantly, their low cost. The only threat to their continued widespread use is the possible environmental consequence of the vast amounts of CO_2 released into the atmosphere as a result of their combustion. The use of fossil energy has raised the level of CO_2 in the atmosphere by roughly 30% since their earliest use, and emissions could reach 10 times current levels in the next 50 years as populations grow and the standard of living improves worldwide. Thus, mitigation of these CO_2 emissions is becoming an important global issue. P-25 is participating in a Laboratory-wide program to apply scientific expertise to the CO_2 issue. Our proposed solution to this problem is to react CO_2 with common mineral silicates, which exist in quantities that far exceed the world's coal reserves, to form carbonates like magnesite or calcite. These reactions are exothermic and thermodynamically favored under ambient conditions. Thus, this disposal option can easily address the CO_2 problem in a safe and permanent manner that also promises to be relatively inexpensive. We are currently participating in experiments with other Laboratory divisions to demonstrate the soundness of this proposal.

Education and Outreach

P-25 group members continue to be active in education and outreach activities, both as participants in programs sponsored by the Laboratory and as individual citizens who volunteer their time for various activities. Recent group member activities include acting as judges for the New Mexico Supercomputing Challenge, serving as consultants for the Teacher Opportunities to Promote Science (TOPS) program, participating in career days and college days at New Mexico schools, and visiting local classrooms. We also coordinated, organized, and participated in the Teacher's Day at the annual meeting of the American Physical Society's Division of

Nuclear Physics.

In addition to these outreach activities, P-25 sponsors several high school, undergraduate, and graduate students to work on projects within the group. Through their individual schools, these students study computing, engineering, and electromechanical technical support, as well as physics, and they supplement their learning through interaction with Laboratory mentors and real on-site experience. Several students are writing theses based on the work they do at P-25.

Further Information

All of the research described is aimed at increasing our understanding of subatomic reactions, and we are poised to make exciting discoveries in nuclear and particle physics over the next several years. To learn more about these projects, as well as the other work being conducted in our group, please see the project descriptions in Chapter 3. Some of our major achievements are also covered as research highlights in Chapter 2. These include our work in high-energy nuclear physics and proton radiography.